A Comprehensive Approach to Complex System Product Development:
Operations Management Tools applied to Automotive Design

By

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To Ghulam Hanif

…who I do and always shall aspire to become

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Thank you
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Abstract

The research is based on observations made over a two-year period with the Closures Systems Integrators or CSIs (supervisory engineers who coordinate attribute balance and system decisions for conflicting door attributes) at a North American automobile manufacturer, focusing on organizational and technical improvements in product development. The product development (PD) process for vehicle side doors forms the case study. A Design Structure Matrix model was made of the process by which important closures attributes are managed through PD, Stamping, Manufacturing and Plant Teams. The attribute delivery process is very tightly coupled with many interactions and conflicts between the attributes, and careful system integration and interface management are essential. The study highlights the need for standardized designs and processes to create time for these system-level tasks, along with better knowledge and resource management. Critical inputs for system attributes are identified and it is shown that a lot of rework occurs if these inputs are changed. The Datum Flow Chain method is developed as a way to communicate data, help with assembly decisions and manage interfaces between component owners. An investigation of issues experienced at product launch shows that programs with CSIs have fewer design- related problems during launch, but that CSIs still spend too much time on Design and Release-type tasks for components (instead of a system focus) and fire-fighting. An extensive organizational study reveals the need for more leverage and clearer roles and responsibilities of CSIs. Conclusions on the process are supported by a simulation model and interviews with CSIs and many other engineers. Simulation results also show that adherence to official product development schedules timing is inherently difficult due to the structure of the as-is PD process. A brief comparison to Toyota's closures design process is also part of the thesis but was not part of the project itself. Recommendations for improvement include a set of design tasks that should be standardized, types of analytical tools that should be developed and managerial practices to be followed.

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1. Introduction

"It's a miracle that we are able to deliver a working product after four years of chaos, to which the biggest contributing factor is that we design components, not systems."

– PD Engineer

Despite contributions of researchers and experiential knowledge spanning several decades, large corporations continue to struggle with staying at the leading edge of product delivery. Complex system product development continues to present some of the most interesting and challenging problems for academic research and practical applications in operations management. Product development is a cross-disciplinary approach, often combining management science with engineering methods. This research attempts to enhance the knowledge regarding design and delivery of complex engineering systems.

The Concept of System Engineering

Most engineering products contain anywhere between several hundred to several thousand parts. Considerations such as cost, manufacturing and assembly also increase the level of interactions between various sub-systems of an engineered product. The exercise of a comprehensive flow down of specifications is a major focus of systems engineering to manage product delivery. All commercial products have certain overarching objectives called customer attributes. Conflicting objectives (such as weight versus strength) and attributes (such as packaging versus aesthetics) lead to the need of system engineering, which addresses attribute tradeoffs or conflicts beginning at the start of the PD process.

Complexity of decompositions and flow downs

In order to successfully deliver and sell most of today's products, their complexity must be defined, understood, predicted and [Calvano and John, 2004]. A major goal for the product development process is to predict system performance, and deliver designs that adhere as closely as possible to the prediction.

The key issues addressed through a product development process include:

1. What are the customer attributes for the product?

2. What are the functional requirements to deliver those attributes?
3. What design options are available to deliver the functions, and which is best?
4. Would it be possible to feasibly manufacture, assemble and repair a final product?

Answers for above questions are fairly straightforward for simple systems. A few relatively large systems (such as electrical) can be reduced to manageable sub-groups that are assigned to separate sub-teams needing minimal coordination once component targets are set. A design approach using a set of "black boxes" can be adopted for simple systems. Most modular circuit systems such as VLSI fall under this category, where a top-down or hierarchal approach to design can be adopted and errors discovered in the design phase. [Whitney, 2004]. Detailed decompositions of design for functions in simple products are not necessary. Consider the case of a paper clip versus photocopier – the former may be hard to divide in simpler components, but it is necessary to separately think of the sub-functions and sub-systems of the photocopier, such as paper feed, image capture and printing. [Ulrich and Eppinger, 2000]. Decompositions depend on functionality, which also defines complexity and PD processes.

Complex systems, with low level of modularity and nonlinear behavior of components after assembly, are different. For most mechanical products, system design is inseparable from component design and a large amount of resources are dedicated to studying side effects and special modes [Whitney, 2004]. Such product designs require a systems approach from the start; otherwise failure is guaranteed.

System level targets for attributes are always defined (such as amount of force required to operate a sub-system, amount of noise created or vibration induced). However, the true challenge lies in meaningfully decomposing such complex systems to represent component-level functionality and flowing down system targets to component level targets. Interfaces between two or more components or sub-systems also need specifications defined for signal exchange, material flows, and energy flows. Moreover, design work has to be completed within the constraints of cost and time. Some of the customer attributes might conflict with each other, calling for a methodology to prioritize decisions.

Challenges in managing complex products

In complex systems, the end result is more than the sum of its parts [Ottino, 2004]. Complex products have complex conceptualization, design, fabrication, testing and manufacturing steps. Most design processes are complex and nonlinear with multiple ideas and decision points evolving before a final design emerges. Product development processes involve high technical complexity and multiple organizations and partnerships (including vendors and customers), making it an inherently difficult process to manage [Schneiderman, 1988]. It is found that most research work on complex products addresses either the technical development process (such as task precedence) or behavioral issues (such as creation of effective cross-functional teams) separately, with little emphasis on their linkages. However, much of the complexity in product development arises from the technical and organizational interactions [Ford and Sterman, 2003]. For instance, after an engineering task is completed, management approval steps or late intervention can increase the complexity of development process. This research investigates the linkage between management and technology and presents some results.

Need for a systems approach

Following challenges in a typical design process for complex products that call for a systems approach:

Predictability: It is usually not predictable how much time each task will take and what the cascading effect from delays is for the whole process. In the end, a product has to be delivered to the customer in a limited timeframe that requires processing of several interrelated tasks simultaneously. Despite a large number of engineers and dedicated resources, most complex product development processes struggle to keep up with competition or customer needs. Some task decisions are guessed to meet deadlines. Also, while component level behavior might be well-understood, system interactions are considered unpredictable – a characteristic of complex system products. Lack of knowledge accumulation and systems approach only further aggravates these issues.

Constraints: Constraints are inherent to the process. No matter how strong the organizational foundation and training for concurrent engineering, certain tasks can only be performed at given times and orderings. In terms of controllable factors, there are capacity constraints that lead to further challenges in managing the process, whereby high capacity utilization can tip the system into perennial firefighting mode that deteriorates process and product quality, and can eventually lead to a point of no return.

Coordination: Much of product development activities entail non-value add delays and communication [Morgan, 2004], but are difficult to avoid based on task coordination and process flow needs. Additional difficulty in managing hand-offs of tasks leads to loss of knowledge and repetition of work that has been done before on the same or similar product. Organizationally, many cross-functional teams, such as design and manufacturing, have to coordinate closely together, without creating work flow hurdles, which is rarely the case. Teams are often set competing objectives or have different reporting chains. These issues further highlight the need for a systems approach. A systems approach gives a holistic view of the PD process to address the issues of process constraints, unpredictability of system behavior and coordination at the component design level. Using simultaneous engineering or system integrators (as will be discussed in detail in later chapters) is one way of implementing a system-oriented approach.

Opportunities to deliver customer attributes

The systems approach provides an opportunity to deliver attributes and manage processes. Only in product development is there sufficient leverage to successfully deliver a system as per its specifications. Product conceptualization phase needs to account for important system decisions because manufacturing phase is too late to introduce changes upon failures. In fact companies that "get it right" during product development usually emerge as winners and cause major losses to competitors that do not – consider the case of Boeing versus Airbus. This is true when time to market is critical, as in the auto industry.

Example of system design and management in auto industry

As an example, an automobile might have system-level metrics such as fuel economy, acceleration time and turning radius. However, specifications must also be created for several dozen sub-systems that make up the automobile such as body, engine, power train (for fuel economy and acceleration), transmission, braking system and suspension (for turning radius). Similarly, engine specifications can include peak power, peak torque, fuel consumption at peak efficiency and peak speed. One challenge is to ensure that sub-system and component level specifications are accurately defined in a way that if these are met, overall system target compliance is also ensured [Eppinger and Ulrich, 2000]. Today's process management reflects following characteristics of dynamic complexity in system-level aspects:

a. Lateral influences dominate hierarchal relationships between components or tasks
b. Cause and effect of system-level or process performance are not obvious or direct
c. Behavior is nonlinear where small deviation from design process has large effects
d. Implication of unproven or non-standard design decisions is much less predictable
e. Risks are dominated by system decisions that are difficult to bound and establish

The automobile as a highly complex product

The automobile would satisfy any process- or architecture-based definition that exists for complex systems. [Weiss, 2003] At a typical US automotive plant, 2,000 to 3,000 workers produce some 250,000 cars per year, working at some 600 work stations with cycle times of 60 seconds or less. The process starts with stamped metallic parts that are welded together to form a body, to which thousands of other parts are attached in less than 24 hours [Fisher and Ittner, 1999]. This is only the tail end of the automotive value chain. It has been observed that the product development that spans system-level design, component design and prototype testing, also needs to seamlessly incorporate process planning from upstream; and manufacturing and assembly implications from downstream. The job of coordinating with stakeholders – internal (cross-functional teams) and external (full service suppliers) - adds on a layer of complexity.

Gateway to the product: side doors as complex systems

One of the most important interactions between the customer and the automobile is with the side door. All conventional vehicles have at least two side doors (such as in the front for coupes and minivans with sliding back doors). Due to the impact on perception of quality, customer satisfaction and a high level of system complexity, doors form the backbone of this research as a comprehensive case study. Despite the evolution of automotive design and development processes, North American companies find it challenging to satisfy all customer needs pertaining to side door performance. However, most Japanese and some European counterparts have managed to strike a balanced system-level approach for design and management that enables acceptable attribute performance on doors, adding interest for this problem.

Literature Review

Similar to manufacturing-related topics, a vast amount of research has been conducted on system engineering, product development, managing technical complexity, organizational change and tools for operations management. This provides a rich foundation for our research project. For systems engineering, work in the aerospace and automotive industry has contributed quite a bit to the field and has been reviewed for the purpose of this research. Calvano, John and Ottino discuss the overarching concepts and implications of systems engineering and complex products. They find that it is best to address system needs as early as possible to avoid cost and quality pitfalls. For product development, Ulrich and Eppinger lay out the fundamentals of what a product design and development process entails. Their work lays out the frameworks of conceptualization and design execution for a new product and utilizes tools such as the design structure matrix. Specifically for the automotive industry, Morgan summarizes inherent challenges in managing complex products such as automobiles by comparing two different companies, one North American and the other being Toyota. His work finds that Toyota uses coordination, standardization and knowledge management to beat its competition on all metrics of product development. Moreover, Clark and Fujimoto provide a comprehensive, case-study based comparison of design process productivity between twenty-two Japanese and American firms. Their findings (from much earlier in time) are quite consistent with what Morgan finds. Sheriff performs another comparative study defining program age and model replacement as success metrics for the automotive product development process. He finds that Japanese companies are ahead for these metrics, followed by German ones whereas US makers lag behind. Cusumano and Nobeoka provide an excellent appraisal of such comparative studies and reaffirm some of Clark and Fujimoto's findings. For the management of technical complexity, research done onsite at a North American OEM is the backbone of analyses within this document. Internal studies clarify how technical interface decisions are managed.

For organizational change, Dr. Janice Klein's True Change written with her work at MIT provides a solid framework for inducing a true cultural evolution in a firm. She finds that an insider-outsider approach to change is an effective way to take a firm forward. In addition, Sterman and Repenning discuss the organizational implications of managing complex product development processes with respect to minimizing firefighting and maximizing program success.

They find that resource utilization and management intervention or practice are key drivers of process performance. Besides literature several formal interviews at OEM site, organizational surveys and culminating (quantitative and qualitative) analyses guide this research effort. For tools in operations management, Whitney and Eppinger rank among the pioneers of the Design Structure Matrix. In addition, Whitney provides a comprehensive theory for the role of mechanical assembly in product development through his Datum Flow Chains model. Suh discusses a framework to approach new products using Axiomatic Design Theory. For dynamic modeling of organizational situations and process behavior modes, Sterman, Repenning and Ford utilize systems dynamic theory and illustrate effects management intervention.

Problem Statement

The thesis comprises a case study at a US automotive company, where data on the product development process for closures (side doors) was collected through reading documents and conducting interviews over a two-year period. The North American OEM that participated in the case study will be referred to as NA OEM from hereon. This research studies the delivery of five system-level customer attributes for side doors, some of which are coupled and directly conflict. These attributes are closing effort, wind noise, water leakage, fit and finish, and chucking (the door bouncing off the latch striker). The system boundary is restricted to the fully assembled door only plus the region of the side of the car body to which the door and its parts directly mate, though interfaces such as fenders and body sides are implicitly taken into account. We examine the whole process for side doors from clay design to manufacturing launch, and analyze key factors that determine the influence on system attribute performance. These include the effect of organizational alignments, engineering tools, system coordination, prioritization methodologies for conflicting decisions, benchmarking, knowledge management, and process implementation among other factors. We apply operations management tools and recommend solutions, both technical and organizational The design structure matrix (DSM) has not been previously applied for managing product development of side door attributes and will benefit this industry. Ideas such as the standardization of best practices and designs are tested through DSM-based process simulations. Another deliverable was to have system knowledge documented in the DSM. For data collections, site visits and observations in residence were made at engineering centers, testing facilities, supplier factories and assembly plants. Interviewees included engineers and managers in PD, manufacturing, plants, stamping and suppliers over two years.

Thesis outline – chapters and contents in brief

The thesis is divided into twelve self-contained chapters. The beginning part starting with chapter 2 will lay out what a product development process for side doors entails and why delivery of door attributes is critical to the success of the overall product. Then, the basics of the case study – side door system – will be discussed in chapter 3, including the components, supply chain and design teams involved. Next, chapter 4 will discuss managerial considerations, coordination and knowledge management or retention.

Subsequent chapters 5, 6 and 7 will cover several technical aspects and insights, including methods of flowing targets, standardizing architectures, using analytical methods and the tools selected in this research, such as the design structure matrix and the datum flow chain. These chapters will also discuss key insights and possible solutions to design management and engineering issues identified during the two-year research project. The ending one-third of the thesis will delve into organizational considerations and important findings. Chapter 8 will cover managerial considerations such as need for incentive creation; effects of late program changes and ideal organizational structure. Chapter 9 will present further organizational analyses, for example structure, integration and reporting chains of teams, based on the design structure matrix. Chapter 10 lays the foundation of implementing the key findings by covering details on the process of change management while leveraging the existing culture of a firm. The last two chapters, 11 and 12, wrap up the study by summarizing outcomes and concluding with recommendations for process improvement to deliver customer attributes for complex products.

2. Holistic View of Side Door PD

"If you want to study an automotive system that is critical to our sales performance based on customer perception and reflects what goes into the process of making an automobile, then pick side doors for a level of complexity that is simply amazing." - *PD Manager*

This chapter contains descriptions of what a PD process entails, definitions of door attributes and drivers of performance on these attributes. Data-based observations on how customers react to attribute performance and comparisons of OEMs regarding door system attributes are also given. As in the Introduction, following is a summary of characteristics of PD processes:

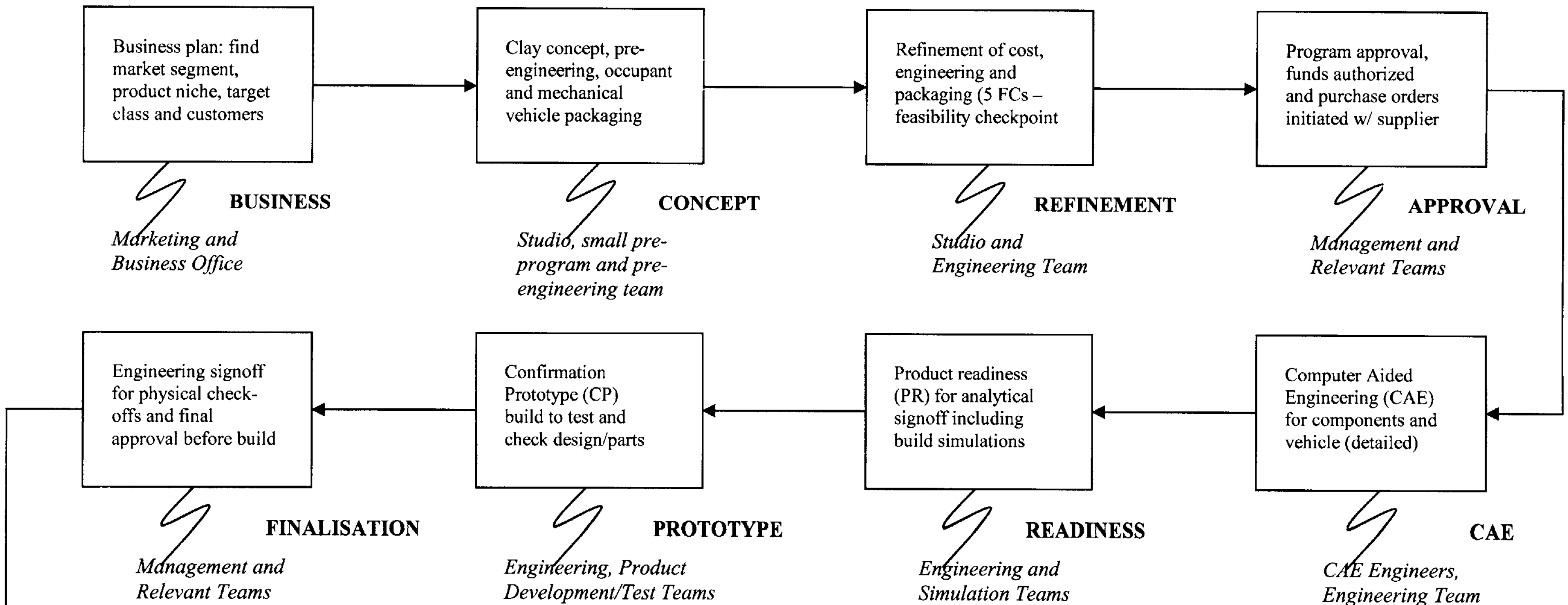
1. Modeling and prediction tools are only as good as the rigor and discipline with which a PD process is defined and followed. For most companies, it is rare that the actual steps overlap with laid out plans and milestones. In fact, it is common to face disastrous setbacks.
2. In the PD process Data, information and product flow is often nonlinear and multi-directional. Much of the work is iterative, cyclic or converging in nature [Morgan, 2004]. Data are exchanged and revised multiple times between sub-teams (unlike manufacturing)
3. The size (at least 400 engineers) and diversity of product development teams is phenomenal because the process requires many technical disciplines or functional activities

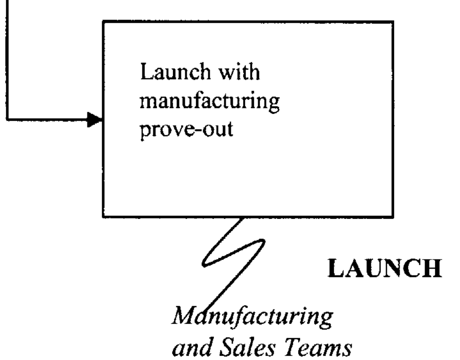
Let us further understand the goals of a door PD process by looking at system-level goals, corporate effects of attribute performance and industry trends for these metrics

Typical value chain in product development

Product development is affected by multiple stakeholders and this is far from trivial to represent. In addition, the impact on the process is different based on the stakeholders' contributions to: cost, timing, quality, sales and team morale. Each product development stage above entails the parallel functioning of several teams, which will be discussed shortly. Following is one possible schematic diagram depicts the operational links in door systems' value chain (the feedbacks are not represented, however the value chain does not flow sequentially. In reality for figure 2.1, there is always some feedback information sent back upstream that could change the earlier contributions or decisions of stakeholders):

The Car Door Value Chain: Design and Launch Process Mapped to Stages and Teams





NOTES:

- The arrows above simply show accomplishment of major milestones and substantial entrance in to the next processes, and are not intended to represent a flow chart. There is information flow between all nine boxes. For example, there are several iterative steps between marketing and business, studio and pre-engineering teams for the business, concept and refinement
- Feasibility checkpoints in refinement is a five step process whereby design evolves from 2-D to 3-D
- Most or all of the design oriented decisions for systems like doors are made in the refinement and readiness processes
- Specifically, about 85-90% of the functional requirements and design parameters for doors are determined in refinement
- The rest (10-15%) is determined between CAE and readiness
- The main role of the prototype is to find flaws and make sure everything is fixed before finalization and launch
- Manufacturing is involved in decisions with PD mostly starting from the approval phase till the launch stages

Figure 2.1: Overview of Operational Activities – Value Chain of Door Delivery. Source: Observations at NA OEM

The product development and delivery phase of the value chain can be summarized as follows in figure 2.2 (Source: Observations at NA OEM in the 2005 – 2007 period):

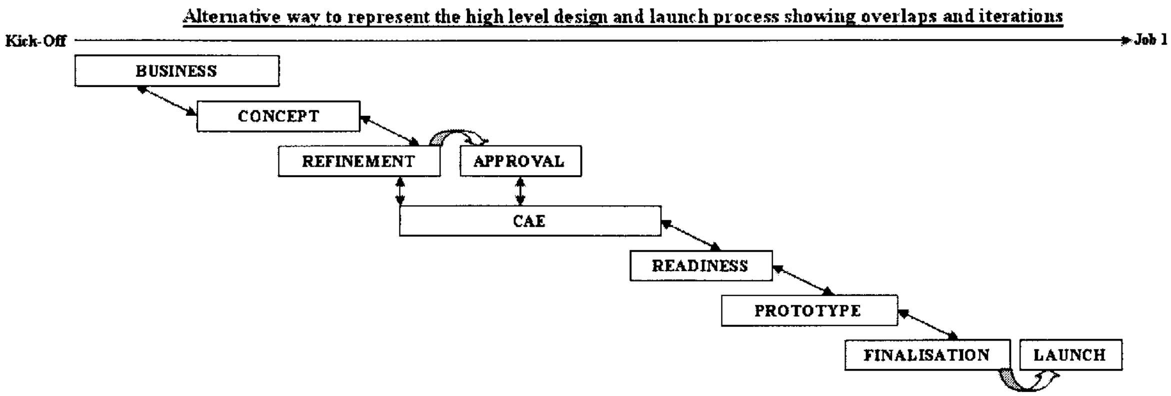


Figure 2.2: Condensed overview of OEM Operational Value Chain

The activities above culminate in the following numbers for the automotive value chain in its entirety (note bottom-up nature of breakdown below) [Andrea and McAnlinden, 2002]:

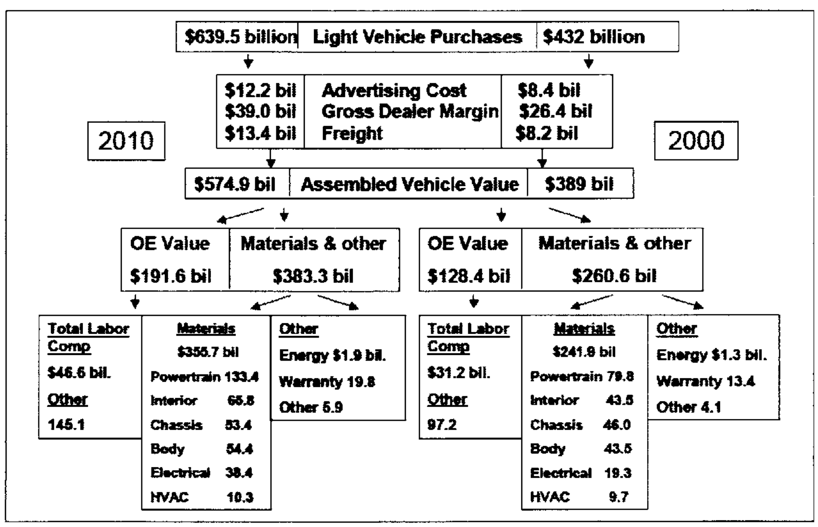


Figure 2.3: From Auto Value Chain to Monetary Data. Source: CAR Altarum Institute, 2002

Although the above dollar amounts in figure 2.3 are pertinent to the whole automotive product, side door systems are expected to follow a similar operational activities and financial breakdown. We now move on to discuss the organizational teams within the OEM involved with the delivery of the door system.

Organizational clusters involved in delivery

Design Studio: this cluster is where design conception and class 1 (exterior) surface definition starts. A design studio entails initial design engineering, math modelers and CAD programs for surface development, studio designers and color developments. In an ideal PD process, the studio would work closely with design engineers and manufacturing experts to design a product that is feasible to produce.

Product Development: The closures (side door) PD team also interacts with other functional teams such as climate control or vehicle interior. The PD teams for NA OEM falls under functional management structure. The PD team is responsible to develop the sheet metal structure while fulfilling all assembly requirements, finalizing closing hardware, meeting cost/weight targets and delivering door attributes in conjunction with interfacing clusters. The PD team has final design, release and signoff responsibility. The Closures Systems Integrators (CSIs) at NA OEM are members of the closures PD team and lead the effort to design doors that achieve their attribute targets.

Attribute Teams: Similar to the closures PD team discussed above attribute-based teams are part of vehicle engineering (VE) that falls under functional management structure. For the case of side doors at NA OEM, there are two specific attribute teams: Squeak and Rattle (door chucking) and Wind Noise. The other attributes fall directly under the PD team. A detailed illustration will follow in a later section.

CAE and CAD: at NA OEM, these teams provide technical support to the PD team, which focuses on engineering decisions. The Computer Aided Engineering (CAE) team runs models on noise vibrations and harshness (NVH – including wind noise inputs), safety (crash) and structures (FEM et cetera). The PD engineering team uses this information for early design and is not allowed to perform its own computer aided design (CAD) work. This is different from Toyota where PD teams work on CAD. The CAD team utilizes expert body designers for illustration, weld design, and tool development tasks.

Suppliers: these also fall under the functional management structure and provide all or most of the parts on door system bill of materials. Some suppliers are involved only with the prototype stage, others with the production stage and a few with both. For sheet metal, soft tooling suppliers are important in sheet metal testing milestones and test builds, while hard tool suppliers provide production stamping dies. This is different for Toyota, which produces a vast majority of hard tooled production dies by itself. [Morgan, 2004] In addition, closing hardware, trim mechanisms and seals are all sourced to full service suppliers for all OEMs. Suppliers work very closely with PD and Stamping teams (where applicable).

Stamping: this team interfaces with PD and manufacturing to determine and approve sheet metal parameters for stamping, such as number of dies punches, draw depths and draft angles. Assessment of stamping feasibility is a critical task in the design process. Stamping falls under Manufacturing cluster.

Manufacturing: there are several sub-teams performing a host of functions. Pre-program team performs initial feasibility studies for body and final assembly. Prototype engineers work with new model assembly facilities during the design stage for proof of concept. There are also production experts for body assembly and final trim The dimensional control group under manufacturing is in charge of all dimensions variation analyses used to set tolerances in the design stage. In addition, manufacturing also assign engineers to work with the PD and plant clusters. Stamping and manufacturing teams' role in product delivery at NA OEM is not as strong as companies like Toyota. [Morgan, 2004]

Testing Facilities: relatively small, localized teams lead OEM testing facilities. These include body test labs for structural testing and wind tunnels for noise performance. Experts are assigned to durability and corrosion, proving grounds, prototype plants, water leak testing and cold chamber for temperature tests.

Assembly Plant: also falls under functional management. Basically, once the product is launched at the NA OEM (and most others), PD and Manufacturing teams leave the plant facility. The responsibility to continue delivering the product as prescribed by PD team then completely falls on Resident Engineers at Plants (called REPs in the rest of this document for brevity). Their responsibility includes fixing issues reported by dealers through warranty.

It is important to realize that at least at the NA OEM in case study, and possibly at other American OEMs, there is an implicit hierarchy of organizational clusters as follows, with program finance at top:

Finance → PD → VE (attribute-based teams)→ REPs (plant teams) → Manufacturing

We now move onto the discussion of specific inputs that affect performance on attributes.

Overview of customer attributes for doors

The door system's high-level functional requirement is to isolate the interior cabin of the car from the external environment. The system has to meet manufacturing and assembly requirements, and satisfy the following customer expectations on performance: good appearance, ease of closing, no water leaks, and quiet interior in all driving conditions.

Definitions and measures of attributes

Following attributes are the most important to customers and the success of car programs:

Wind Noise: This is defined as the amount of the wind noise that is audible to the passengers as a vehicle is subjected to dynamic conditions. As the car is driven, noise is generated due to wind resistance and aspiration. Aspiration occurs when the top part of a door's frame bends away from the car's body side. At high vehicle speeds, the external pressure around the window frame of the door is lower than the internal cabin pressure. The dynamic load on the door frame pulls it outwards. This may lead to the separation of seals and create a path for air to leak out of the car's cabin, creating a whistling noise, also know as aspiration. The amount of noise generated through air resistance depends on the aerodynamic and shape characteristics of a vehicle, the stiffness of the door system and sealing strategy. The problem of aspiration noise can be created or worsened by each of the following factors:

i) Manufacturing and assembly variations: if variation in seal gap is biased towards the high side, it can aggravate the noise problem even if the build variation falls in the designed range.
ii) Vehicle Speed: The faster the speed of a vehicle, greater the chance of door blowout.
iii) Angle of Approach: If high speed wind (due to high driving speed or wind speed or both) approaches the door at certain angles, the door header is more likely to bend outwards.

Other factors could influence wind noise as well, for instance the age of the door seals. Wind noise is usually measured in decibels, which captures intensity of sound; or sones, which is perceived loudness.

Closing Effort: This is defined as the minimum amount of effort it takes a customer to close a side (revolving as opposed to sliding) door from the outside of the vehicle. The performance on closing effort attribute depends on how well the system-level interactions of design inputs, including seal parameters and closing hardware (like hinges), are understood, and whether tradeoff decisions are correctly made.

Similar to wind noise, performance on the closing effort attribute is also mostly determined in the design stage. But if seals are not mounted correctly or do not retain the designed position, seal interference could increase, causing higher closing effort. Closing effort is measured in meters/second (velocity, which captures door momentum); or Joules, which is a unit of energy required. Other possible units include pounds (lbs) to measure force. Amount of effort to close doors could be worsened by:

i) Manufacturing and assembly variations: the effect on closing effort is analogous to that on wind noise based on seal gap variation. If gap is smaller than the designed variation range, the amount of seal interference upon closing the door increases (and vice versa).

ii) Closing conditions: if the vehicle is tipped against the direction of swing, it would be more difficult to close the door. Also, closing hardware can fail in extremely cold environments.

iii) Paths for Air Flow: if all the windows and air vents for climate control are closed, it would be more difficult to close the door as opposed to the windows open condition. This is because the action of closing a door generates a pressure wave by compressing air in to the cabin as the door finishes closing. This pressure wave exerts a force on the door's inner side when the latch is just about to engage. Typically air pressure factors to contribute approximately 40% to the total amount of effort required to close a door. Air path management is important.

Water Leaks: this is more of a straightforward attribute with binary states – whether or not water from outside enters through side doors and reaches the vehicle cabin. Typically, water leaks are easy to detect and are considered unacceptable. Water can accumulate in drain channels between the vehicle door and roof, and collect in pockets around the door seals. If water management and drainage schemes fail, the water can drip inside the cabin upon opening the door. Under dynamic conditions, water leaks can occur due to rain from the same reason as aspiration wind noise from seal separation. Leaks are worsened by:

i) Manufacturing and assembly variations: as expected, dimensional variations in individual parts and in assembly could lead to water leaks; for instance, if seal gaps are too wide.
ii) Vehicle Speeds and Angle of Approach: this is the same as wind noise (from blowout)
iii) Water drainage paths: if the drainage paths for accumulated water are not carefully designed.
Other factors that affect water leaks involve consistency and accuracy of mounting seals at assembly plants, ageing of seals that reduce stiffness/interference and permanent door sag

Craftsmanship – Margin and Flushness: this is a relatively subjective attribute for aesthetic appeal and appearance of a vehicle in assembly. As per observations at the company under study, because no particular design team is assigned the responsibility of hollow space (such as that determining the margins attribute), Margin is defined as the dimension of the gap between door outer panel and fender, roof, A/B pillar or adjacent door. Margin variations are caused due to the up-down and/or fore-aft dimensional error in assembly. Flushness measures whether the door is coplanar (in the in-out direction) with fender, roof, A/B pillar or adjacent door. Flushness is reported as a dimension for the relative position of the door outer panel and corresponding surfaces. Any variation from the nominal design in which the door is not flush to all other surfaces in most cases leads to a variation in seal gap from the nominal. Deviations from nominal values of flushness that affects seal gap and corresponding attributes. As a summary, following influences could possibly affect margin and flushness performances:
i) Production capability vis-à-vis design: Dimensional variation analysis (DVA) uses plant data, design details and computational software to help predict final variations. This, combined with GD&T rules renders an expected capability (Cp or Cpk) that is used for design purposes. For instance, a margin target might be set at 5 +/- 0.5 mm, where the variation range is an expected one and used to ensure door functionality (such as swing feasibility). However, and especially for North American manufacturers, it is not uncommon to have production capabilities that are lower than design capability.
ii) Mean drift in dies and tooling over time: this is usually due to poor maintenance.
iii) Interfaces for margin and flushness: in some cases, margin is defined by an appliqué (plastic)-metal interface, there is more likelihood of errors in part dimensions.
Other factors could include unrealistic targets based on design, simply because management and engineering divisions never came to an agreement on feasible margin/flushness values.

Squeak and Rattle – Door Chucking: this is defined as the amount of noise generated due to vibrations induced in the door system as the vehicle is driven over a rough surface under various speed and road conditions. The noise is usually a result of metal to metal impact for components in the door due to:

a. Latch-striker: hard contact parts in latch with engaged striker due to vibrations

b. Sheet metal-sheet metal: contact of door structure to body side –happens rarely

c. Hinge flaps: high frequency and amplitude vibrations can generate noise at hinges

d. Components in door trim: any loose components like window motor could rattle

e. Window glass: under constrained window could rattle in glass run and create noise

Likelihood of meeting targets on the chucking for door(s) is worsened by the following:

i) Manufacturing and assembly variations: if seal gaps are on the tighter side of variation, a reduction in noise and chucking is caused at the expense of closing effort (and vice versa).

ii) Deviations from assembly process: loose components go unnoticed and cause chucking.

iii) Component key life and ageing: reduction in stiffness of latch bumpers causes chucking. Other factors include reduction in seal compression as vehicle ages. Door chucking measurements at a system-level are largely qualitative and depend on train engineers to test the vehicles on rough tracks.

Definitions of design inputs for attributes

The OEM in this case study has a few documents identifying attribute delivery tasks or design parameters (called attribute inputs), like the following inter-dependency matrix as a systems guideline:

Functional Req vs. Design Parameters	Air extraction (controlled)	Extraction though leakage (uncontrolled)	Leakage through handle	Leakage through belt	Leakage through glass runs	Check Energy	Seal interference	Seal CLD	Seal CLD set/loss	Hinge axis tip	Hinge axis alignment	Hinge torsional energy	Latch force	Glass penetration	Door frame stiffness	Seal gap variations	Margins variations	Flushness variations	Hinge pillar stiffness
Minimise Variable Cost									x							x	x	x	
Minimise TGW	x	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x	x
Maximise GQRS Score											x					x	x	x	
Minimise water leak			x	x	x		x	x	x	x	x			x	x	x	x	x	x
Minimise Repair Cost																x	x	x	
Meet life requirement			x	x	x						x	x			x	x	x	x	x
Minimise Squeak & Rattle						x	x			x	x		x	x	x	x	x	x	
Minimise Windnoise		x	x	x	x		x	x	x	x	x			x	x	x	x	x	x
Minimise Closing Effort	x	x				x	x	x	x	x	x	x	x		x	x	x	x	x
Optimize margin flushness										x	x				x		x	x	x

Table 2.1: Sample system document for attribute management. Source: Internal NA OEM, 2006

However, as will be discussed later, most of this knowledge is in engineers' minds. For instance, the document in table 2.1 does not contain all critical inputs to door attributes. Moreover, the information flows amongst the entries in top row are not captured. The ordering of the list is not in terms of time or importance based sequence. In addition, design guides related to the contents of the table shown are very limited. Therefore, another form of capturing the above information more holistically would be needed.

Inputs within door system boundary

In this case study, the door system comprises all components (most of them on the door except some such as air extractors) that determine door attribute performance. Several inputs that affect door attributes are related to these components; however certain inputs are different from typical design parameters for example computer-based analytics, physical tests, and feasibility studies on assembly.

When the door is closed, primary and secondary seals compress and exert a reaction force on the header section. Typically, the header section (A-frame) of side doors is not stiff enough to withstand these forces and bends outwards. Consequently, design engineers trend set the header position to be bent slightly inwards so that the nominal position is flush to the body side in closed-door position. This pre-defined bending in of headers part of the door is called 'cheat'. If the door is not cheated to the right amount, the header could be slightly outboard from nominal position and oncoming wind is more likely to blow out the door, causing wind noise. The number of seal walls (that is the number of seals around the door) determines the likelihood of wind noise and water leaks. Similarly, aspiration leaks can occur between the top section of window glass and header if the glass penetration into door frame is not sufficiently deep. It is difficult to seal the gaps between the window glass and the beltline section of the door (horizontal partition between window cavity and the sheet metal part below door header). KBE (knowledge based engineering and CAE software models, along with several bench tests help assess the predicted and actual performance on important design parameters such as seal interference and amount of header deflection or stiffness. Engineers need to carefully design how seals are mounted and retained around the door on the door or body sheet metal. In addition, noise or leakage paths can develop through gaps where the window divisional bar mates with the door header or beltline sheet metal.

Some effort-related inputs also affect wind noise. The closer the door's center of gravity to hinge centre line (an imaginary line joining the two hinges), the smaller the momentum build up for a given amount of effort and harder to close the door. The angle at which the latch approaches and engages the striker also affects amount of closing effort – ideal trajectory of approach of the latch is parallel to the striker so that the latch pawl (rotating internal part) impacts the striker head-on for minimal engagement force. Usually, all seals are designed at some extra amount of stiffness to compensate for compression set and stiffness loss from ageing. Moreover, as the seals are squeezed upon closing, the air trapped inside is compressed and counters the closing action, for which vent holes are designed into the seals. Dimensional Variation Analyses (DVAs) using software and program data determine the amount of seal gap variation that is compensated by using larger seals. Door sag (permanent deformation in vertical direction) also affects closing effort because the customer needs to transfer enough energy for the door to be lifted upwards as the latch opening hits the striker at a lower than nominal position. The design for sag and drop-off (from the door's own weight) is driven by physical tests. In addition, door sag is less likely to occur during the lifetime of the vehicle if the body side is stiffer and hence sealing would be more effective. In the case of permanent door sag, seals do not contact the intended surfaces and sealing effectiveness is compromised. Stiffness of the bumper inside the latch that squeezes against striker also affects closing effort. Lastly, actions taken to improve sound quality can also improve closing effort

The amount of water leakage through the barrier of the door system is too complex of a phenomenon to model. Instead, the NA OEMs (and most likely others) depend on actual testing in the prototype and launch stage (where capability data are collected in production). Most of the preceding design steps are carried out with the belief that designing for wind noise essentially takes care of water leaks because of the need to seal the door system from a higher pressure fluid flow in the case of wind noise.

Platform assumptions (determining the volume of door trim space) and even minute dimensional inputs such as paint thickness affect margin and flushness targets. Margins are affected by door swing feasibility assessments to avoid hard metal contact that could block door closing and flushness is also affected by accuracy of door cheat predictions. Also, the farther apart the hinges (or larger the hinge spread), the less the effect of assembly error due to geometric relationships. Similarly, a higher vertical position of striker geometrically favors the likelihood of better door assembly. Variations and craftsmanship interfaces also play a key role. For instance, it is more feasible to accurately predict and control the margin or flushness between metal-to-metal interfaces as compared to a plastic-to-plastic. Chucking is more centered on the latch component design and parameters because the latch-striker combination essentially constrains a rotational degree of freedom that would lead to rattling noises if improperly constrained. Dynamic sealing (primary and secondary) parameters also play a role. In addition, physical tests help determine the level of performance and appropriate design changes if needed to meet chucking targets.

Inputs external to but related with door system

Several other design inputs have an effect on door attribute performance, but only some of the most important ones are mentioned below with a brief description:

Body side stiffness – hinge pillar and striker mounting surface: Although door system stiffness is listed as a direct input to wind noise above, stiffness of the body side to which the door assembles also determines how much blowout would occur in dynamic loading.

Body side dimensional variation: The most direct effect of high variations in body side dimensions is on seal gaps (for primary and secondary). This affects all attributes in consideration.

HVAC Duct Seal: There is an HVAC (also known as climate control) duct passing from vehicle front end control panel to window glass through the door inner panel. In order to seal this interface between door and front end, OEMs usually place a donut-like stiff seal on the door and body side. Depending on the stiffness parameters and dimensions of this duct seal, closing effort may be affected.

Wiring Grommet/Harness: A plastic or rubber wire harness, which is similar to a hollow flexible tube, is used to pass all electric wiring between the front end body side and the door trim internal mechanisms, such as window motor. This wire harness passes through the door inner close to the HVAC duct. If the wire harness stiffness is on the high side, as is the case some times, closing effort might increase again.

Roof Ditch Design: The design of the water drainage 'ditch' along the roof affects the collection and management of water that might drip into the cabin upon opening the vehicle door after rainfall. Roof and body side drainage paths affect static water leaks.

Front End Shape: The aerodynamic properties of the vehicle affect the amount of wind noise generated directly as a result of air drag and the amount of blowout in door header that causes aspiration noise.

Air extractor design and position: Air extractors (at the backside bumper) help in the release of pressure wave in the cabin during the action o closing the door, and assist in reducing effort to some extent. Similarly, extractors play a role in equilibrating the internal and external pressure in dynamic conditions.

Drivers of attribute performance

Though not very well understood at NA OEM, it is known that the pressure wave caused by compressing air in the vehicular cabin opposes the closing motion of a door. It is common to use air extractors to help this. It is also found that closing effort on rear doors is higher than front doors. One reason is that hinge tip angle that assists in closing is not as high as it is on front doors. Another reason is that the swing angle is different from front doors and increases the effects of any striker misalignments to latch. It is not coincidental that rear doors have more warranty issues reported – usually as high as twice the number of issues reported on front doors for OEM under study.

The next largest contributor to closing effort is the amount of energy required to compress the seals to their resting position after the door is closed. Here, it is important to note that tradeoff decisions with the wind noise attribute become critical. Thicker and stiffer the seals are better for noise and leaks attributes. As per interviews, both closing effort and wind noise rank high in warranty costs for North American OEMs. Design for craftsmanship targets entails meticulous swing and package studies, optimization of assembly sequences and error stack-ups, and minimization of component variations. Component design (based on bench top experiments modularized design and performance metrics cascaded to the lowest level) determines the extent of door chucking for the most part. Satisfactory performance on wind noise guarantees satisfactory performance on water leaks. Good performance on craftsmanship and wind noise leads to acceptable performance on chucking.

Macroscopic effects of attribute performance

Good attribute performance reflects successful process management for product development, manufacturing and assembly steps. An OEM that struggles with satisfying customers with product performance is usually caught in a firefighting mode that leaves no resources for operational improvements. This is particularly true for body engineering. Poor attribute performance leads to low level of organizational learning and team morale. When it comes to buying a car, one would expect the customers to mostly care about engine properties such as horsepower and fuel consumption, styling and durability. Surprisingly, performance of side doors for attributes discussed above turns out to be critical as well. At the OEM where the case study for this research was conducted, extensive data analyses show that wind noise ranks as most important (by definition), while door chucking ranks lowest.

Customer satisfaction, warranty costs and sales

Not surprisingly, customers are willing to take the time to report issues with side door attribute performance and bring in their complaints to dealers. A squeaky or hard-to-close door on a new vehicle prompts the customer to feel the product was not worth their expenditure. This affects both current warranty costs and future sales. Once the vehicle comes to the dealer, the repair action is logged and reported back to the OEM. A simple fix, for instance one blow with a hammer on a misaligned striker causing high closing effort, could run a bill of $75 for the OEM (labor is usually charged at this hourly rate). The cost is higher if latches have to be lubricated or hinges need repair work. When it comes to fixing noise or leaks related issues such as having to remount door seals, a few hours of labor is reported and charged at a minimum, if not a new component charge on top. The OEM for this research's case studies has reported warranty costs of anywhere between 2 – 4 times the cost of its immediate competitors. Once a customer builds an opinion about door performance, brand image and quality perception, it trickles down to the whole market through surveys such as JD Powers. In addition, OEMs usually mail surveys to their customers who bought a new vehicle at certain points in time after the sale. OEM data show a significant and positive correlation between current customer satisfaction and future sales, and a significant negative correlation between warranty costs and satisfaction or future sales.

Perception of quality and brand Image

There are several ways in which door attribute performance determines the success of a vehicle program. For instance, the harder a door is to close, the more likelihood that internal components in the door would rattle and render poor closing sound quality (although this is not the focus of our study). Similarly, any aspiration noise or water leak while driving would signify poor production quality.

Word of mouth and consumer surveys would capture these data, only to further reduce brand image and hence affect product sales. Sound quality of a vehicle while driving over rough surfaces at high speeds (such as city roads) also leaves a perception of model luxury and comfort in the customer's mind. These effects stem from the fact that a vehicle's side door (besides steering column or gear) is the most commonly used interface for a customer. If the hood is hard to open or close, the customer might suffer once a week. If there is such an issue with the door(s), the customer lives it at least once a day.

Trends for Side Door Attributes

OEM performance on side door attributes has significantly improved over the last couple of decades, such that tweaking of parameter and deep diving into analyzing and defining customer metrics is commonplace. The industry has come a long way to provide the lowest levels of wind noise and closing effort, and continues to improve. Similarly, door margins are becoming tighter, flushness improving and water leaks are generally a story from the past. Billions of dollars have been invested in assembly and plant process improvements, such as optical dimension recording machines for quality control. Such industrial trends have led to better door systems and high customer expectations, especially with the availability of several brands and dozens of models in the marketplace.

Leading customer surveys such as JD Power show customer complaints for two key attributes of wind noise and closing effort are generally higher for American OEMs than their Japanese or German counterparts. This leads to the question of whether the tolerance bands and specification limits used in the capability calculations are realistic and consistent for all OEMs, and the answer probably is no, as shown in figure 2.4 [CAR, 2001]: (data collected in a study of door design/manufacturing performance)

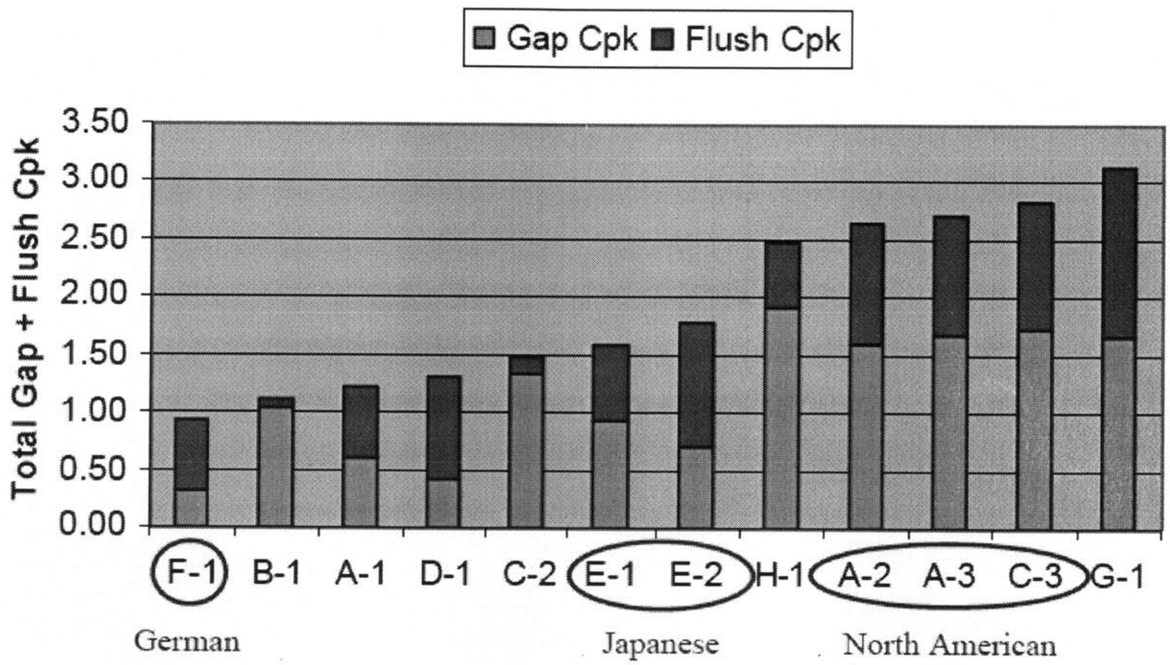


Figure 2.4: Seal Gap/Flushness Capability [Source: Center of Automotive Research, 2001]

Customer complaints are associated with dimensional variation. On the other hand, Cpk is calculates through dividing the achievable dimensions by allowable tolerance range. The allowable tolerance range for North American manufacturers is generally kept at a higher value than their Japanese counterparts. Therefore, a high Cpk for a North American company can still translate to a higher variation than a Japanese OEM. As explained, dimensional variation in flushness and/or seal gaps deteriorates attribute performance. Several factors are involved. For instance, a considerable amount of variation is added between the body shop of a plant and final assembly for American OEMs. So much so, OEM A-3 has one of the best individual parts Cpk (not shown in figure 2.4) but one of the worst attribute (gap and flushness) performances, as discussed later. Owing to these facts, Japanese companies in particular and some luxury European manufacturers show faster improvements in attribute performance than American firms. For instance, Toyota and Honda lead for effort, while Audi and Honda for craftsmanship.

Customer expectations

For wind noise, customers expect relative quietness in the vehicle cabin under all driving conditions. In fact, customers are known to define wind noise performance by how high they have to turn up the volume in their vehicle to listen to the radio while driving. There is lower tolerance for aspiration noise from seal separation than noise from wind drag. An energy transfer of 8-9 Joules is deemed to be a good target for closing effort at NA OEM. However, door-to-door variation effects can negate a low average amount of effort per door. If a vehicle is at 10.5 Joules per door, with very little variation (less than +/- 0.5 Joules) of closing effort required from one door to the next on the same car, customers tend to perceive the car as having better performing doors for effort than, for instance, if the average was 8.5 Joules with a range of 7.5 – 10 Joules depending on the door. If such a prioritization is necessary, OEMs are likely to better meet customer expectations by choosing to focus on door-to-door variation effects than reducing the average. Customers expect zero water leaks. Best in class margins for doors target a 3.5-4mm range. For chucking, customers expect no major sounds extraneous to road noise and vibration.

Attribute performance metrics

The following shows the result of a recent analysis for 2005 calendar year Things Gone Wrong (TGWs) that are reported through warranty data at dealerships during repairs [OEM, 2006].

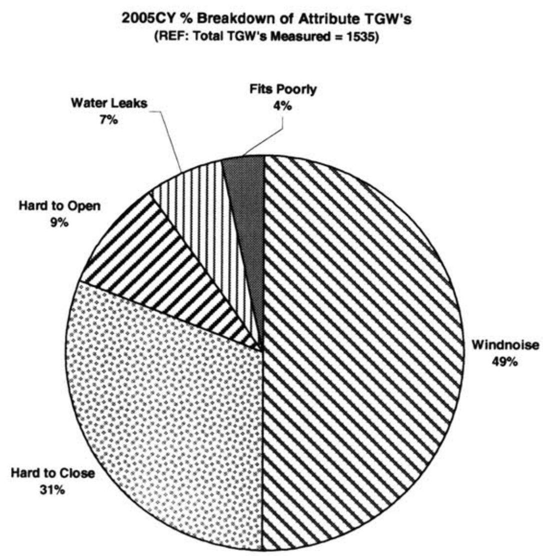


Figure 2.5: Things Gone Wrong (Warranty Complaints) [Source: NA OEM, 2006]

For NA OEM as shown in figure 2.5 above, wind noise and closing effort are the most important issues as expected. However, it is interesting to see that both attributes have such high TGWs. An almost equally unsatisfactory performance on two directly conflicting attributes points to a lack of system-level coordination and decision-making in engineering without considering attribute tradeoffs. The existence of water leaks points to the inadequacy of vehicle inspection methods for soak tests in water booths at assembly plant. Margin and flushness attribute is being delivered to a high level of customer satisfaction.

Performance of American, Japanese and Other firms

The performance of European luxury brand manufacturers tends to be higher than American automotive companies, primarily because of higher selling prices, greater program budgets and consequently more design levers such as higher quality of seals. Control on dimensional variation enhances performance of Japanese OEMs. Following show American versus Japanese performance [CAR, 2001]:

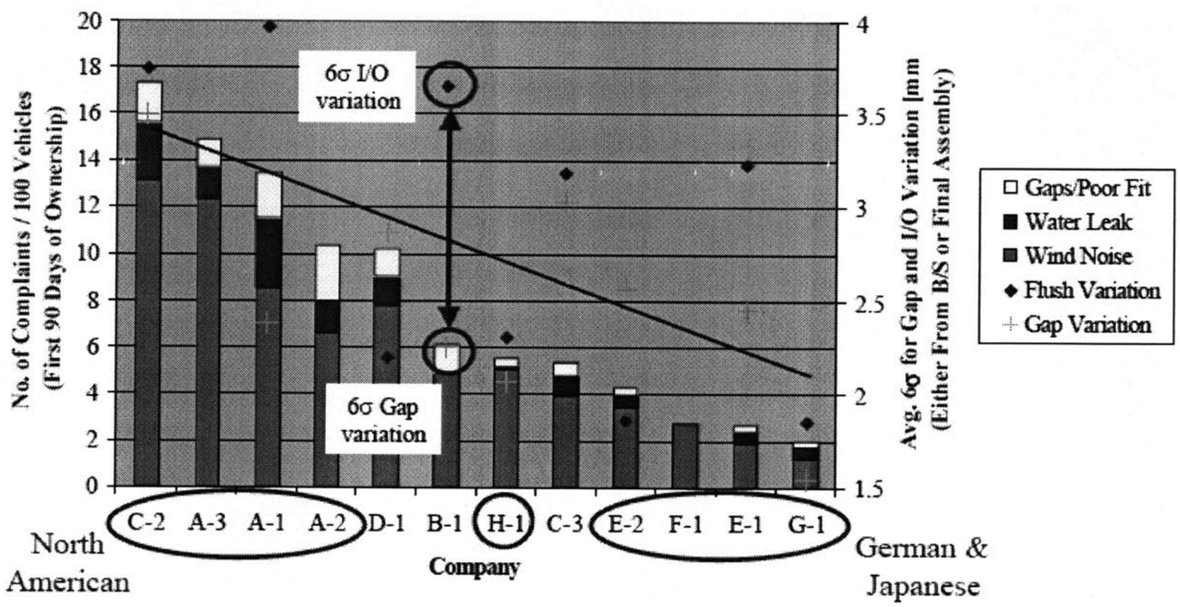


Figure 2.6: Customer Attribute Complaints [Center for Automotive Research, 2001]

From figure 2.6, appears that North American OEMs are on the higher side of variation for both seal gaps and flushness, which is consistent with door architecture and assembly. There is a significant and positive correlation between gap or flushness variation and issues with wind noise and water leaks (also closing effort depending on directionality of variation). Customers are very sensitive to these attributes and often report issues back to the dealers. These are reported as Things Gone Wrong (TGWs), a list that is topped by the conflicting attributes of wind noise and closing effort for NA OEM. This means that the company is neither biased to outperform on one attribute, nor positioned to balance the attributes to satisfy the system expectations of customers. Consequently, the perception of quality and sales are affected. North American companies generally lag behind Japanese/German OEMs.

However, American OEMs are improving. In this chapter, we learned that the PD process to deliver door attributes needs to account for several system decisions. Door attributes are complex in terms of the number of factors that determine performance. Manufacturing variations in the assembly stage and tradeoffs such as seal forces in the design stage are some of the biggest drivers of attribute performance. In the next chapter, there is a deep dive into the basics of the door system – technical and organizational.

3. Basics of Side Door System

In this chapter, the contributing physical components, critical dimensions, design teams and design inputs that determine performance of side door attributes are laid out. In addition, a brief overview of the door delivery supply/value chain is presented.

Key dimensions, key characteristics and sheet metal architectures

For the various systems and components, KCs are defined as parameters or features in a part or system that are important for customers, sensitive relative to design function or reliability, or critical or historically difficult to control during manufacture and assembly, thus requiring special attention. The KC selection process is begun by defining functional and reliability targets during the approval phase of a new product, and can come from teams such as Body Engineering. During the various stages of development, OEMs also define measurements and methods to evaluate the KC selection. If control plans are created during the development phase, they can ensure KCs chosen will be controllable.

Teams that are responsible for the selection of KCs are divided based on the vehicular assemblies, sub-assemblies, and components. The sequential hierarchy of an OEM's management in general needs to also be reflected with the flow down to component teams. This is not the case at NA OEM and system roles are not well-defined (more later). For the case of door attributes, the degree to which the following key characteristics (in terms of dimensional relationships) are achieved determines PD success: Primary seal (on door inner panel) to door body side, Rocker seal and secondary seal (on body side) to door inner panel; Door outer panel to body side. The first two KCs affect wind noise, effort and water leaks while the third affects margin and flushness. We discuss the types of door architectures in industry below.

Sheet Metal Assembly and Door Architectures: A vast variety of car doors, almost three-quarters, are still of the conventional stamped full inner and outer type. This is particularly applicable to

US automotive industry; however there is expected to be a gradual shift towards separate window (A) frame, which is more common among Japanese OEMs such as Toyota. It is generally believed that a separate window frame enables more dimensional control over the door sheet metal assembly and helps in functional build. The separate frame itself is roll-formed metal that has high stiffness. Illustration of the three door architectures is shown in figure 3.1 below [CAR, 2001]:

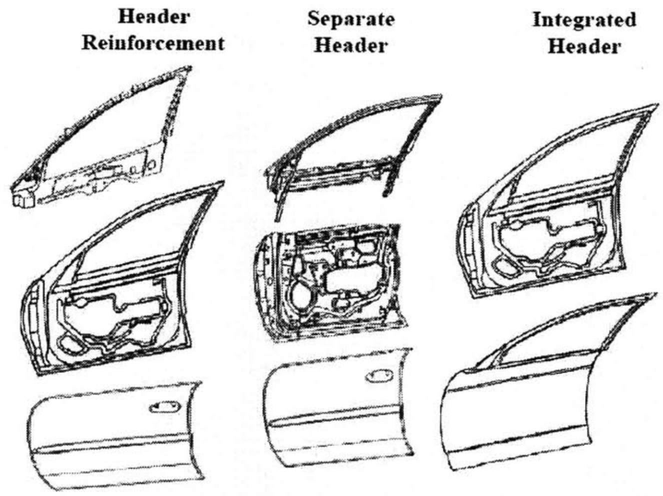


Figure 3.1: Three dominant door architectures. Source: Center for Automotive Research 2001

The horizontal surface of sheet metal below the header is called the beltline and (along with the header) forms the boundary around the (closed) window glass. When separate, the header is welded to the sides of the beltline on lower half of the door. The lower part of figure 3.1 shows the outer panel in three architectural configurations, and the upper two parts form the inner panel.

Door-related components in attribute performance

In the physical domain, the door system for the sake of this case study is defined as all components that assemble (mate) to or contact the door inner and outer panel, including relevant portions of the body side panel. In the design domain, it is defined as all design decisions, test procedures and analytical checks that determine and deliver resulting performance for five door attributes. Consequently, components that affect one or more attribute directly are below:

Primary and Secondary Seals: as shown in the cross-sections in figure 3.2 on the next page, these are rubber seals mounted around the door. The primary seal is what incoming fluids (air or water) encounter. Primary and secondary seals typically have the following cross-sections [from NA OEM Full Service Supplier, 2005]. All doors would have at least the primary seal (left) and secondary seals (additional ones depending on program strategy – all rest except one on left):

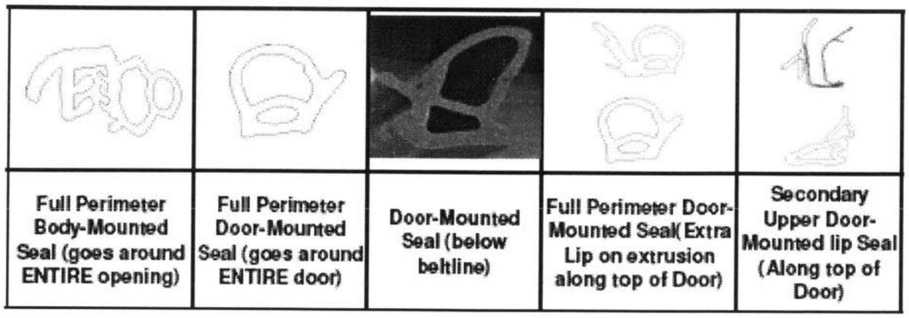


Figure 3.2: Cross-section of primary (first) seal and secondary (other) seals cross-section

Latch: The function of the latch is to engage a striker for retention of the door in closed position. The latch has to meet operational and safety requirements. The rotating part of the latch that turns over and engages the striker is called the pawl. Figure 3.3 shows a typical latch assembly [Honda, 1990] available by searching Honda latches at http://www.shopping.yahoo.com:

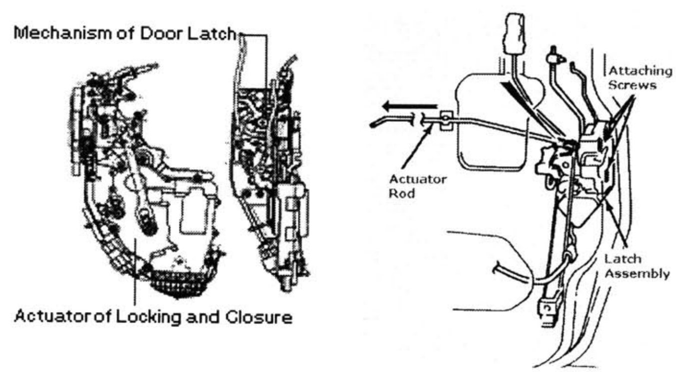


Figure 3.3: Latch (cross-sectional) view and assembly features on latch component

Striker: A rotating part inside the door latch engages a striker when the door is closed. The striker (U-shaped hook) is mounted on body side and the accuracy of its position in assembly is critical as follows:

- Up-down variation in striker position affects closing effort and possibly margins
- In-out variation in striker position affects flushness and seal gaps (leaks or noise)
- For-aft variation is not a common occurrence because striker rests on body side

Air Extractors and Their Position: An extractor is a vent or valve with a rubber flap covering the rectangular holes. When the air pressure on the inner side rises above the ambient (e.g. air conditioning or closing door), pressure equilibrium is established over time by air leakage through the extractors:

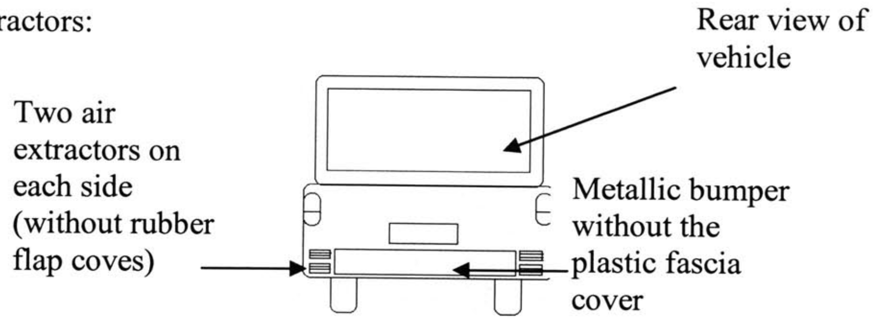


Figure 3.4: Location of air extractors on vehicle body

The extractors are fitted in cavities in the car body shell as shown in figure 3.4 previously. The air inside the car first has to pass through small holes (~25 cm^2 or less) before it reaches extractors.

Hinges: The function of hinges is to enable door assembly on to the body and allow swing of the door. If a plant uses a doors off process (taking doors of the body to install components after paint shop), the inner and outer flaps of hinges are separable. Hinges look like the following in figure 3.5 [CAR, 2002]:

Figure 3.5: Hinge view in assembly

Hinges are also one of the components that could be standardized across all programs.

Checks: The door check that holds an open door in pre-determined positions can add to or assist in closing effort, depending on the design of check arm profile and opening radius. The check design has no bearing on any of the other door attributes.

We now review the automotive supply chain. In the auto industry, the supply chain is a highly complex one and has been studied extensively to gain insights into process (cost, time and performance) management. Before reaching the final assembly stage, door components come together from hundreds of supply sources that use all conceivable manufacturing processes.

Typical supply chain for door components

The US automotive supply chain is a capital intensive one, with consumers spending 5% of their income on vehicles or parts and US vehicles accounting for hundreds of billions of dollars or about 10% of total value of manufactured goods [Department of Commerce, 1998]. An all-new (including platform) program takes $2-3 billion to develop. A typical vehicle has on the order of 15,000 parts [Tassey, 1999]. Infrastructure suppliers provide software, hardware, tooling and robots to all levels of the supply chain. The US automotive industry is less concentrated and more competitive in the downstream segment of the supply chain. Suppliers to major automotive companies could be broken down by sizes in figure 3.6:

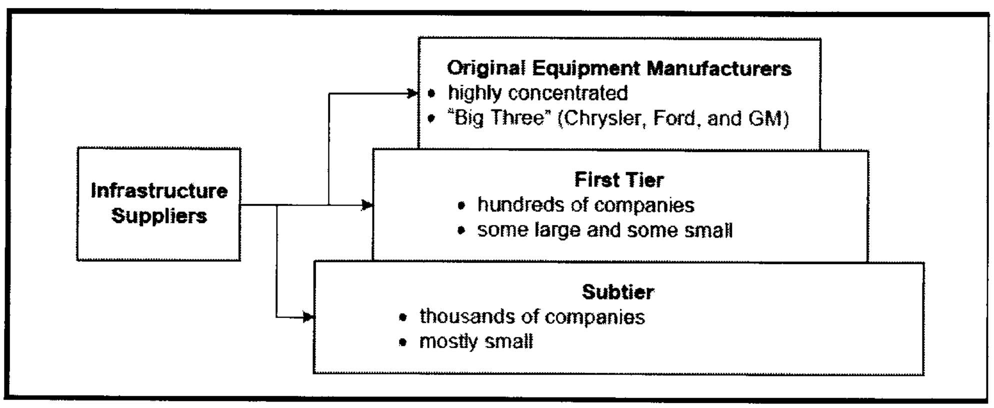


Figure 3.6: Hierarchal arrangement of suppliers. Source: Triangle Research Instt, 1999

Body design is a highly complex process that would theoretically require a vertical integration of the supply chain [Novak and Eppinger, 2001]. Standard parts could be bought or outsourced, whereas complex parts ought to be produced in-house for best system results. However, the door system supply chain is highly disintegrated, which adds to the complexity of managing design decision, changing component specifications and determining system-level tradeoffs. In American OEMs, the PD team generally serves as the backbone of the supply chain. This is slightly different from the Japanese OEMs that not only outsource more, but also integrate manufacturing/assembly teams more in the supply chain.

Clark and Fujimoto [1991] and Clark [1989] explain why Japanese OEMs are able to outsource even a higher percentage of components and treat them as "black boxes": there is much more part standardization, a much stronger link between manufacturing and design and consequently an advantage in project cost and lead time for Japanese OEMs in comparison to North American ones. For North American OEMs, a relatively disintegrated supply chain combined with a cluster-based organizational culture adds to the requirement for door PD team to act in a system integration role.

Attribute and design ownership in case study

In this section, we show that having multiple attribute owners residing in different teams or clusters makes it difficult to coordinate decisions that affect conflicting system attributes. NA OEM needs to be conscientious of this organizational structure and its affect on the process so that the right level of system engineering and coordination can be implemented through initiatives such as closures systems integrators and new ideas for simultaneous engineering. Following are some details.

Wind Noise: is owned by wind noise team (falling under noise, vibration and harshness – NVH cluster), and this attribute based chain is similar to that for door chucking (falling under squeak and rattle – S&R cluster).

Because the attribute resides with a specialized team, wind noise receives considerable amount of resources and time during all stages of the PD process (as compared to closing effort for example). The wind noise attribute is reported as follows and the CSI position also interfaces with the chains:

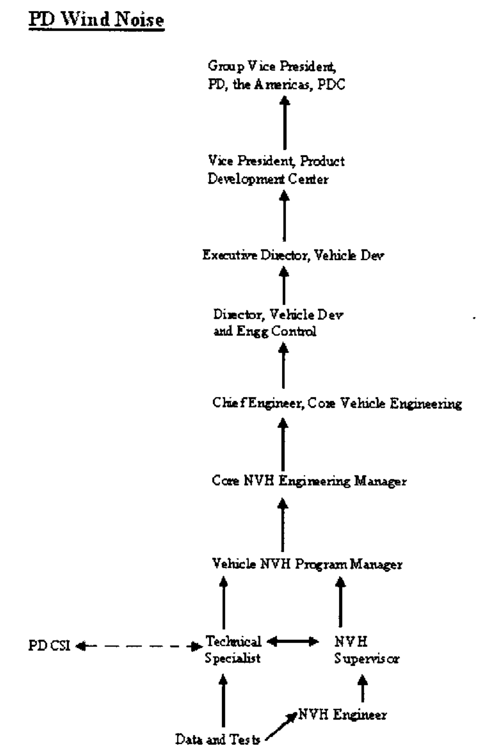


Figure 3.7: PD reporting chain for Wind Noise (doors). Source: NA OEM

Closing Effort: this is owned by door PD team (sheet metal), and reported as follows:

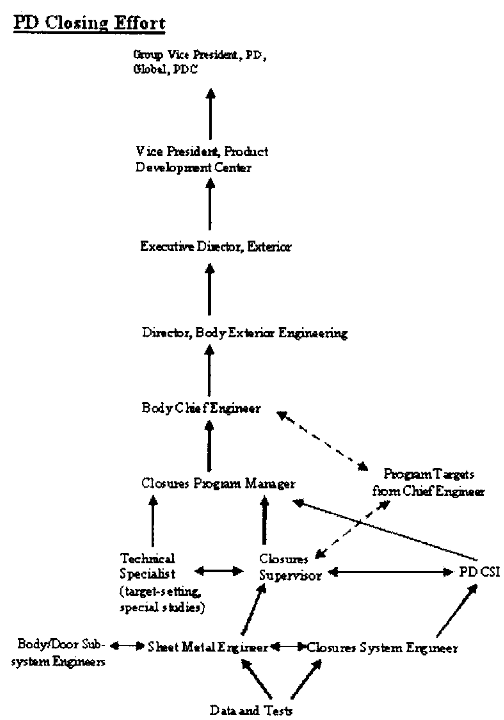


Figure 3.8: PD reporting chain for Closing Effort (doors). Source: NA OEM

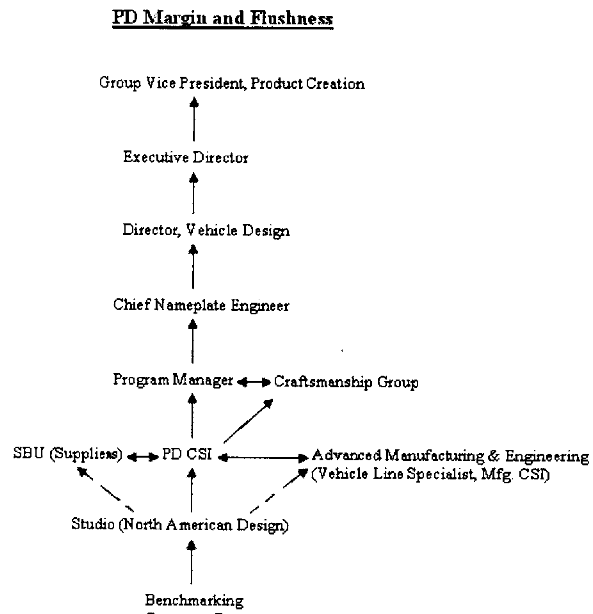


Figure 3.9: PD reporting chain for Margin and Flushness. Source: NA OEM

Because of this, multiple teams are responsible to deliver at least their part of the attribute.

Door Chucking: this attribute is owned by the squeak and rattle team and is reported as:

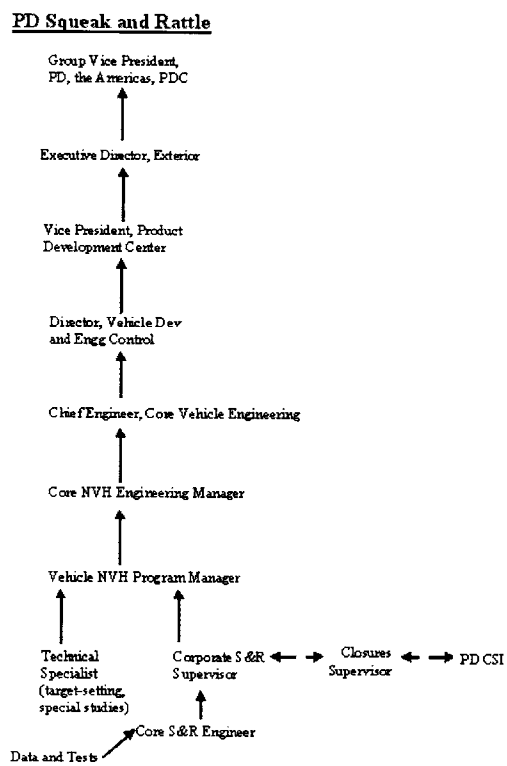


Figure 3.10: PD reporting chain for Chucking (side doors). Source: NA OEM

Water Leaks: is owned by every stakeholder, and there is no official reporting chain for it.

Note the existence of the CSI or Closure System Integrator role in all chains (details in later chapters). It is observed that wind noise and door chucking have one reporting structure, and the other three system-level attributes fall under different managers. This increases the challenge of coordination.

After design and prototype testing stages, the responsibility of monitoring and delivering attributes (including fixing of warranty-related issues) lies with the production team (REPs) at the assembly plant. However, there is no coordinator (like PD CSI) to balance attribute-related decisions at plants. At the same time, assembly plants at NA OEM also have disparate attribute reporting chains to monitor fixes to warranty issues. This potentially sets a stage for uncoordinated decisions across in-plant teams. The next chapter presents a discussion of knowledge management for a successful PD process.

4. Knowledge Management

"We do not attempt to capture knowledge with any systematic or centralized approach. The DSM and network results show systematic methods to consider interactions. DSM interviews have also given me more things to think about upfront before firefighting."

– Closures Supervisor

Principles from proven process management theory can be utilized to understand and potentially improve product development performance [Morgan, 2004]. However, such improvements can only take place by using the scientific method and targeting incremental learning that becomes intrinsic to the process. In addition, process and product-related knowledge management is critical in two ways: good knowledge management ensures better quality on current programs through sharing of expertise and implementation of lessons learned; and good knowledge management is a key enabler of PD success. In this chapter, we make some important observations for knowledge management at the NA OEM, draw some conclusions about the nature of underlying PD process and make comparisons with other OEMs, such as Toyota. Knowledge management includes the following [Interviews at NA OEM, 2005-2007]:

i) Benchmarking, customer survey and market trend data for setting the program's direction and overarching objectives for the system

ii) Accessible design details such as system architecture, component parameters and extent of compliance to the process from past programs or related models to reduce amount of reinvention of the existing knowledge that is scattered

iii) Identifying customer attributes and critical dimensions (for system) to define targets and key characteristics with tolerance ranges, to be met by appropriate design decisions

iv) Critical component-level inputs to system level attributes to be used as design levers for delivering a product that meets or exceeds customer expectations

v) Guidelines on making component level tradeoffs, in particular when one component or design parameter contributes to two or more attributes with opposing directionality (called attribute conflict) to avoid acceptable performance on one attribute at the expense of another

vi) Interactions (design information flow, energy exchange, special constraint et cetera) between components to determine the sequence of design decisions

vii) Cross-functional considerations such as stamping approval, manufacturing cost, assembly feasibility and best practice criteria for product development in order to avoid late changes

We now present the state of knowledge management at NA OEM for this case study.

System design guides and documentation

A system design guide in the form of paper reports or online information would provide the knowledge discussed above for each component that contributes to system performance, and serve as a blueprint on how to design the product at a detailed level. A good system design guide would be continually used and updated through the documentation of existing system information and updating it with new knowledge developed. Moreover, such a design guide would trace each component-level decision back to the system-level attribute and point out any attribute conflicts that might exist At NA OEM, the bulk of design steps are driven by guides called system design specifications (SDS). There is an SDS for each design parameter and after extensive review, it has been found that each SDS provides the what(s), i.e. targets for design process. One major deficiency encountered is a lack of system knowledge (such as effect of component parameters on attributes or attribute balance) and program experience (such as lessons learned or best practices) captured. Besides online portals where the SDS guides are posted, there is no central database with documentation of guides as they ought to be – the how(s) of design.

An initiative to create one central website by technical specialists has not attracted much attention. The idea behind this portal is to capture how recent programs have made their design decisions and why they have chosen a particular design from options available. This knowledge-based site is now a mere skeletal structure with barely any meaningful content. as day-to-day program needs use up the time available to engineers. Given the fact that some of the engineers are switched out from closures design roles after two to three years, their experience is lost with their departure. Those who are able to stay on in the same role as before for new programs have to reinvent whenever a new situation arises.

Good practices vis-à-vis current situation

Companies that excel in PD and in the market have clear knowledge management practices. Going back to the basics of engineering, executing fundamental principles at the cascaded component-level and building back up to system-level goals for a product is critical for the success of manufacturing firms. As such, Toyota has established itself as a global leader in product development. Toyota follows four rules for its process design and improvements, as follows:

The Four Rules

The tacit knowledge that underlies the Toyota Production System can be captured in four basic rules. These rules guide the design, operation, and improvement of every activity, connection, and pathway for every product and service. The rules are as follows:

Rule 1: All work shall be highly specified as to content, sequence, timing, and outcome.

Rule 2: Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.

Rule 3: The pathway for every product and service must be simple and direct.

Rule 4: Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.

All the rules require that activities, connections, and flow paths have built-in tests to signal problems automatically. It is the continual response to problems that makes this seemingly rigid system so flexible and adaptable to changing circumstances.

Figure 4.1: DNA of knowledge and change at Toyota. Source: Spear and Bowen, 1999

The author of this research thesis argues there is a feedback loop between good knowledge management practices and product performance. None of the above four rules carry any weight without tacit knowledge management at both the component and system level. At Toyota, as mentioned, knowledge is developed at the lowest organizational level possible and centralized to be applied across programs.

There are three reflection points in the Toyota process to promote organizational learning and continuous improvement. 1) The in process reflection designed to reflect on performance to date to expectations and feedback from internal customers, 2) a post mortem or lessons learned type reflection that takes place at the end of each project and finally, 3) a personal reflection assignment focused on a specific aspect of an individuals performance usually assigned by that person's direct supervisor. These built-in learning events are a crucial part of Toyota's improvement [Morgan, 2004] There are no such process-based events at NA OEM.

Role of developing and maintaining knowledge

Because of the challenges faced by NA OEM, a special arrangement for developing and maintaining knowledge has to be made. NA OEM has two designated technical specialists within the closures design cluster, who focus on margin and flushness and closing effort. It has been observed that the technical specialists spend most of their work time on special projects upon management's directions or program support. If these technical specialists were designated the task of maintaining system knowledge, it would be the first step in the right direction. Technical specialists could also help document program insights and reduce reinvention during new programs. Chucking and wind noise have designated technical specialists outside the closures design cluster. These specialists spend relatively more time on building and maintaining knowledge for their attributes. This gives one explanation of the priority that has traditionally been given to wind noise for side doors at NA OEM.

Retention of knowledge during handoffs

A well-integrated product development process is set up to minimize the number of handoffs and preserve system knowledge during each handoff that occurs. A handoff involves passing on a design task or critical design information from one sub-team to another sub-team within or outside the boundaries of a functional cluster. For instance in the stamping cluster at NE OEM, the pre-program stamping feasibility team assesses initial sheet metal design for manufacturing for the first time and advises the sheet metal design team to proceed at early stages. The pre-program team then hands off its assessment studies and decision-making power about feasibility to the production stamping team at the vehicle prototype stage (later on). The pre-program team completely phases out and a considerable amount of churn is created through this handoff. The production stamping team often has to redo all the feasibility assessment studies to come up to speed, and often causes the sheet metal design team to make late changes to early details such as locator schemes, number of stamping die draws and draft angles. This is an example of a typical handoff at the NA OEM where system knowledge is not preserved. According to Morgan, the waste from handoffs can be seen easily on the value stream map as a transfer of product between work centers. A great deal is lost in hand offs in NA OEM process. [Morgan, 2004] It becomes even more important for available guides to capture interfaces and interactions besides fundamental engineering knowledge: i) what information is needed to perform a design task, ii) which other teams (supplier/internal) are involved, iii) what information is needed downstream.

Comparison of American and Japanese OEM

At NA OEM, after proving the vehicle prototype, PD engineers in closures spend their last three or four months on a program at the production plant site to 'launch' the vehicle. These engineers have been observed to spend significant time in rework-related paperwork, and visits to stamping plant or toolmaker to fix issues at such a late stage in the program. Information management systems and failure of stamping prove out at the appropriate PD stage leaves minimal time to coordinate with the plant team (REPs) – the resident engineers. A minimal discussion and information exchange was observed between REPs and PD. For example, as of two months before a new program launch, REPs did not understand details of door locator, hinge mounting and door hanging strategies. Yet, REPs is expected to make adjustments to assembly schemes when quality or warranty issues emerge. Besides, manufacturing engineers at this stage under Manufacturing team are process engineers. They focus mostly on setting up assembly lines in time. Product quality is only REP's concern after launch. Though difficult, proper handover to REPs with minimal loss of knowledge is crucial for product success because REPs serves as the funnel for warranty issues. This is quite a contrast to Toyota, where the equivalent of REPs called Production Engineering (PE) is involved in the design decisions. Production Engineers have continuous access to parts drawings as they are being designed by the Body Engineers. Applying value stream maps to the Toyota process shows that going to the heart of an engineering problem with the goal of organizational learning is a driver of knowledge development. [Morgan, 2004] In addition Toyota has a better managed handoff process and centralized knowledge across programs.

The term Simultaneous Engineering is often used interchangeably with Concurrent Engineering in product development literature and could form the backbone of satisfactory system performance by overlapping the functional activities of several sub-teams. [Clark & Fujimoto, 1991; Cusamano & Nobeoka, 1998, Wheelwright & Clark, 1992; Fleischer & Liker, 1997] The Simultaneous Engineering (SE) group at Toyota was created in 1996 to serve as a linkage between Production Engineering and Product Development. The (SE) group is organized around specific vehicle programs. Each program team can range from two to six members each of whom represents Production Engineering. [Morgan, 2004] SE staff is a participant in the PD process and helps balance system-level tradeoffs for attributes.

DSM and DFC for knowledge management

As will be discussed in detail in chapters 6 and 7, the Design Structure Matrix and the Datum Flow Chain trace system-level interactions and key characteristics. The DSM facilitates in sequencing and managing interactions between the decisions involved in a system design. For a PD process, it is a matrix comprising of design inputs and captures information flows and provides a project representation that allows for feedback and cyclic task dependencies. DFCs facilitates assembly design by creating a top-down model that supports how (constraints), where (features) and to what accuracy physical (tolerances) parts are located. [Whitney, 2004]

Tools to identify critical knowledge needs

DSM and DFC are tools to identify critical knowledge needs, which would improve the PD process. NA OEM could utilize these operations management models to manage knowledge. The DSM identifies critical component-level interactions and DFC maps critical physical interfaces.

Comparing knowledge from interviews and guides

As one example, the process of building a DSM could point out where knowledge resides. For building the DSM, the research was started with engineering design and validation documents. Then component engineers were interviewed and system engineers were involved. Following observations were made:

- *Most component-level knowledge is captured in design and test documents*

- *Most system-level knowledge is stored in the mind of engineers (goes up with experience)*
- *Longest interaction chains and largest clusters came from interviewing system engineers*

The amount of time each engineer was able to spend in the interviewing process also contributed to the length of interaction chains in the DSM. However, the amount of system knowledge and experience in the engineers' minds was a significant factor, particularly when engineers had launch experience.

Critical system level interfaces affecting attributes

There is a need to (better) integrate manufacturing systems engineers with design systems engineer. In general, early stage coordination between manufacturing (including stamping), product development and plant teams is critical for attribute management. In addition, the impact of supplier interfaces needs to be incorporated because insights from suppliers (sheet metal and components such as latch) to design issues are not always accounted for but should be considered. NA OEM has started a technical club of system integrators/engineers. [Stevens, 2005] It meets once a week (or less) to share knowledge about critical interfaces and their interactions for door attributes. However, this has been seen to have minimal effect on the system because firefighting on day-to-day engineering tasks occupies the engineer's attention. Efforts like Six Sigma have been helpful but certainly do not fix fundamental knowledge needs. NA OEM needs revisit the basics of the door system and document knowledge with a bottom-up approach. This has recently been acknowledged more seriously by upper management, and will hopefully remain on their radars. [Observations, 2005-07]

The next chapter covers considerations for the management of technical complexity in multiple-attribute projects using various means.

5. Managing Technical Complexity

"We manage complexity day-in and day-out without thinking about it and do an amazing job in getting most technical decisions right purely based on engineering experience. A more systematic approach might lead us to getting all of the technical decisions right."

-Closures Technical Specialist

Technical complexity is a hallmark of new vehicle development, especially in the case of side door attribute management, and arises from the following factors among others:

1. Difficulty in understanding customer attributes to set feasible functional targets
2. Determining component-level targets to meet system requirements for customers
3. Necessity to concurrently meet multiple requirements for sub- and major systems
4. Lack of modeling and prediction capability of system behavior without hardware
5. Disconnects between hardware tests for prototypes and customers' experience
6. Unavailability of standard design architecture or solutions for new program issues
7. Improvement in technologies from competitive efforts and changing market trend

Despite the wealth of engineering knowledge and experience in an automotive firm, technical complexity of the vehicle needs systematic management throughout the PD process. This chapter reviews how NA OEM manages technical complexity through its design process and analytical methodologies, and compares with good practices found at industry leaders such as Toyota.

Targets for side door attribute performance

According to Lockheed's Kelly Johnson's famous rule, Skunk Works engineers must not be located more that a stone's throw from the air plane as it is being built" [Rich and Janos, 1994]. This means physical and intellectual proximity to the product. At NA OEM, most of the attribute targets are simply a legacy and engineers do not understand the origin of these targets due to lack of documentation. Also with routine tasks, engineers spend less than 15% of their time on analysis. Targets for doors are below in table 5.1:

Attribute	System Target	Cascaded to Component-Level
Wind Noise	2 sones	To a small extent
Closing Effort	8 Joules	To a large extent
Water Leaks	Zero	No
Chucking	Qualitative	No
Margin and Flushness	Program (> +/- 5 mm)	No

Table 5.1: NA OEM Attribute Performance Targets (Source: NA OEM Documents)

According to extensive literature available, Toyota believes in going to the source of each problem and each customer demand and closely tying engineers (intellectually, physically and emotionally) to the product. [Morgan, 2004] Toyota benchmarking involves getting a feel for door performance at system and component levels, collecting data and comparing performance. At NA OEM benchmarking analysis performed is qualitative, e.g. observations made at auto shows. Lack of resources is another factor.

Benchmarking, setting and understanding targets

A summary of a typical "benchmarking" exercise at NA OEM is shown in Table 5.2:

Serial #	Vehicle	OEM	Level of Sealing System	Prim. Seal (mm)	Sec. Seal (mm)	Ease of Closing Effort pass? (window open)	Craftsmanship Grade (1 = poor 10 = Best Seen)	Closing Sound Quality	Comments
1	07 SUV	Saturn	1	13	NA	Yes	8	Good	
2	Pilot	Honda	2	11	4	Yes	6	Mediocre	
3	Element	Honda	2	11	6	Yes	4	Poor	
4	Odyssey	Honda	2	13	7	Yes	5	Mediocre	
5	07 SUV	Mazda	2	13	9	Yes	8	Good	
6	Accord	Honda	2	10	10	No	7	Mediocre	
7	Ridgeline Truck	Honda	2	11	4	Yes	4	Mediocre	
8	Civic	Honda	2	9	6	Yes	8	Poor	
9	Fit	Honda	2	9	6	Yes	6	Poor	
10	GC 320 CDI SUV	Mercedes	2	10	5	Yes	8	Good	
11	07 E320	Mercedes	2	11	6	Yes	8	Good	
12	Versa	Nissan	2	10	5	Yes	7	Good	Sash Door
13	Armada	Nissan	2	10	9	Yes	8	Good	Sash Door
14	Frontier	Nissan	1.5	6	9 (half)	Yes	8	Good	
15	Pathfinder	Nissan	2	5	8	Yes	8	Good	
16	Tundra	Toyota	2	8	4	Yes	8	Good	
17	Prius	Toyota	2	8	6	Yes	8	Mediocre	
18	Highlander	Toyota	2	12	6	Yes	8	Mediocre	
19	RX 400h	Lexus	2	12	4	Yes	8	Good	
20	LX 470	Lexus	2	12	6	Yes	8	Good	
21	GX 470 SUV	Lexus	2	12	4	Yes	8	Excellent	
22	IS 250	Lexus	2	14	4	Yes	9	Excellent	Low stiffness
23	ES 350	Lexus	2	12	3	Yes	9	Excellent	
24	Equinox	Chevy	2	14	8	Yes	6	Mediocre	
25	Aura	Saturn	1	12	NA	Yes	6	Good	
26	Silverado	Chevy	1	14	NA	Yes	6	Mediocre	
27	Entourage	Hyundai	2	10	6	Yes	8	Good	
28	Tuscon	Hyundai	2	12	4	Yes	6	Good	
29	Azera	Hyundai	2	10	4	Yes	9	Excellent	
30	Santa Fe	Hyundai	2	8	4	Yes	9	Good	
31	F-150	Ford	1	13	NA	No	8	Good	
32	Escape	Ford	1	13	NA	Yes	7	Good	
33	Expedition	Ford	1	13	NA	Yes	8	Good	

Table 5.2: Typical benchmark data collected at NA OEM (Source: Observations, 2005-07)

In addition, of the 82 inputs (design parameters, computer models and physical tests) identified as contributors to door system attributes, about 50% have no competitor data at all (including qualitative). Therefore, NA OEM engineers find it difficult to understand and set targets from a market perspective.

Product quality is certainly affected at NA OEM, which is not the case at some of their major competitors. For instance, at Toyota, the Chief Engineer's team physically tears down competitor products and familiarizes itself with the components through hands-on experience. [Morgan, 2004]

Cascading targets or flowing key characteristics

Targets and key characteristics need correct cascades not only in the currents state of the market, but also a few years in the future. NA OEM is unable to achieve this for both current and future states of markets. At Toyota, a process based on competitor assessment is used to set specific, component level performance goals for quality and manufacturability by the module development teams. These specific goals are converted to measurable performance objectives by the respective functional organization and performance to these goals is measured at program completion as part of the reflection process. These specific component goals along with the checklists ensure that key characteristics are achieved.

Standardization of architecture and design

One advantage is accumulation of best practice and design knowledge by using standardized components and architecture, while evolving these ever so slightly for each new model year. Cost is another consideration. A comprehensive study at General Motors found out that reduction of part counts and assembly changes (for example by slightly reducing option variability available to customers) by 10% could reduce costs by $14 million per assembly plant per month [Fisher and Ittner, 1999]. In total, the savings add up to hundreds of millions of dollars annually. Some of these cost savings could be re-invested in quality. In addition, standardization is a lever to manage technical complexity as mentioned in point 6 in the beginning of this chapter, with which NA OEM has traditionally struggled.

Role in managing technical complexity

NA OEM's engineering culture is based on innovation and creative solutions. 82 design inputs for door attributes reveal that at least 35% of the inputs have no standardization. The rest that are standardized vary in the level of standardization from procedural (such as side view mirror design) to physical (such as latch design). The low level of standardization coupled with the lack of good design guides (as discussed in chapter 4) leads to following challenges in managing complexity at NA OEM:

i) need to reinvent basic design inputs and to perform all feasibility checks again
ii) waste of process time in avoidable work at the expense of system coordination
iii) unexpected interface issues or system behavior leading to late design changes
iv) lack of focus on process and product improvement and resulting high PD costs
v) loss of organizational learning and competitive edge in a dynamic marketplace

This case study research reveals that NA OEM engineers spend less than 10% of their time on learning and standardization. Japanese OEMs have learned to standardize since the last two decades, because:

a. Standard processes serve as a source of system integration [Morgan 2004]
b. Engineering time is instead spent on improving system performance and learning
c. Standard designs enable functional groups to predict what to expect from others
d. Concurrent engineering is possible when system performance is more predictable
e. Cost, time and rework saving is inherent to self-improving standardization culture

Based on the above, OEMs should standardize various aspects of the door development process:

- Design guides and attribute targets
- Assembly strategies and locator schemes
- Sheet metal architecture and design

We now look at a few more comparative examples from Japanese and NA OEM.

Comparison of American and Japanese OEM

The NA OEM has conducted some sheet-metal studies on hoods to compare with Toyota's standardization in stamping. Results show the following differences:

Toyota:
- Panels are fully hemmed.
- Standard "X" beam pattern.
- Hinge and latch pockets relatively shallow without separate depression (30-35mm depth).
- Size, location and number of holes (locator and insulator blanket attachment) are standardized.
- Standard hinge reinforcement design.

NA OEM:
- Panels are a combination of hemmed (75-80%) and welded down standing flanges (20-25%).
- Non standard beam structure between vehicle lines (X beam, rectangular, etc).
- Deep hinge and latch pockets (up to 85mm from external surface). Hinge locations vary.
- Hole sizes, amount and location vary across vehicle lines (SUV has additional seal, mid-sized has additional lightening and e-coat drain (approximately 20/vehicle).
- Unique hinge reinforcement

For doors, lack of standardization is also clear from NA OEM's closing effort sensitivity to seal gap variation from the assembly process. On some programs, a seal gap variation of +/- 1mm leads to a change of only 1 J in closing effort, or a sensitivity of 1 J/mm. While on other programs the closing effort to seal gap sensitivity is 4 J/mm due to design differences. Unlike NA OEM, standardization tools such as checklists are central to the development process at Toyota and same globally. One example of a product checklist is the "quality matrix". There is a specific quality matrix maintained for each major sheet metal part on each vehicle. That is to say that the Camry fender has its own quality matrix as does the Siena door outer. At NA OEM, such records are difficult to find except for CAD drawings or sign-off sheets. This relates back to the occurrence of reinvention, rework and firefighting. Toyota checklists also serve to integrate systems and coordinate cross-functions. Across the top of a design checklist, all the steps in the manufacturing process are listed. So Checklists may provide crucial steps within a process (process checklist) or guidelines for specific characteristics of a product design (product checklist). Checklists are maintained by the same groups who use them. [Morgan, 2004]. On the other hand, a recent effort at NA OEM to create a checklist to balance door effort and wind noise faltered after much-heated debate for a few weeks. Some engineers disagreed with the scope of the sheet (e.g. which system interactions need documentation), while others expressed inability to comply with extra checklists because of overworked schedules. NA OEM checks all sheet metal parts for stamping formability and die draw feasibility using FEA (finite element analysis) tools. On the other hand, both stamping design and inputs to the FEA tools are highly standardized at Toyota, leading to better quality and lower amount of waste.

We now perform a quick overview of door attribute-related analytical tools.

Tools and Models for Attributes at OEM:

NA OEM uses some analytical tools for prediction and physical tests for confirmation of component and system performance. The analytical tools for closing effort and geometry decisions mostly reside under the Knowledge Based Engineering (KBE) group, while wind noise and door stiffness-related tools are mostly under the Computer Aided Engineering (CAE) group. Physical testing duties lie with attribute owners at the hierarchal level of design and release, as discussed in chapter 3 in detail. The accuracy of prediction tools at NA OEM is questionable, which leads to over-reliance on physical tests late in PD.

DOME and KBE tools

DOME (Distributed Object-based Modeling Environment) is an innovative software infrastructure that is a Web-based, simulation modeling environment to support emergent and integrated design processes such as door design. Users of DOME could quickly create simulations for large integrated systems and predict likely characteristic before implementing prototype systems. NA OEM tested DOME as below:

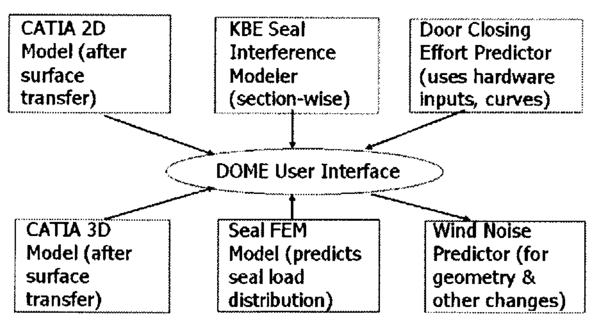


Figure 5.1: Overview of DOME-based door attribute analysis and tradeoff tool

Shown in Figure 5.1, section results from seal interference area (KBE SIM tool) are at best a proxy for overall wind noise attribute. KBE SIM shows the amount of seal compression around the door perimeter, from which the seal forces could be deduced. The tool helps in validation of seal interference and seal gap (including jumps and smoothness). Another representation of DOME plug-ins in figure 5.2 follows:

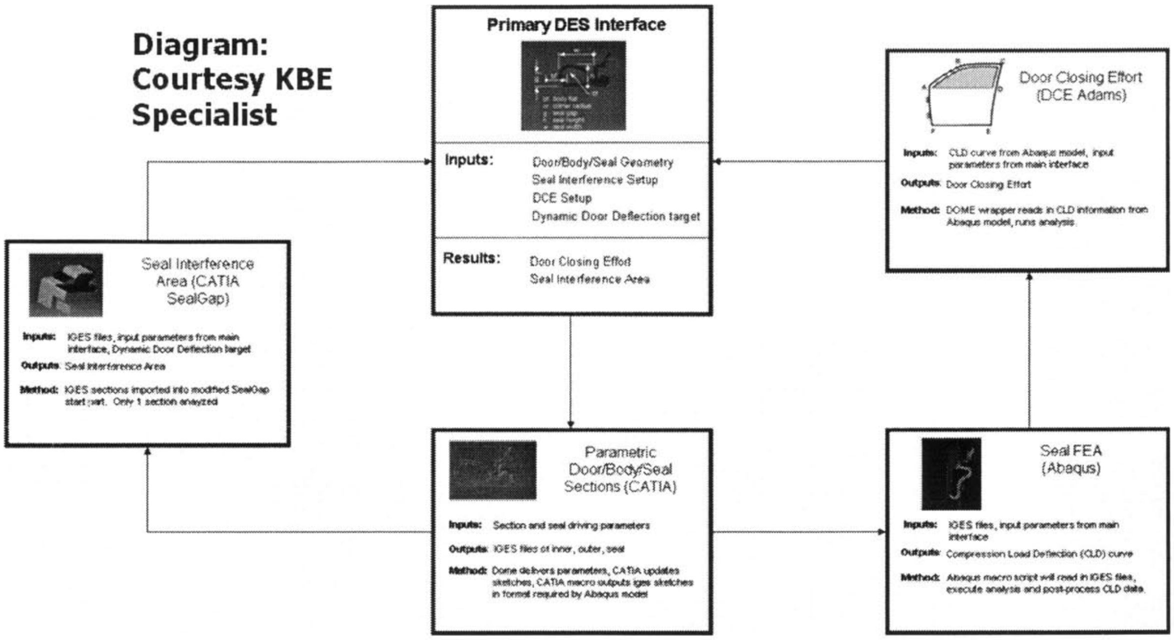


Figure 5.2: Plug-ins for tradeoff analysis using DOME

First version of DOME-based KBE is ready (integrating plug-in tools for tradeoffs). In isolation, the KBE Seal Interference Model (SIM) is used far more frequently than KBE Door Closing Effort (DCE) Model because of certain inaccuracies in the latter. The initiative to improve KBE DCE tool has not seen follow-through to completion. Some of the shortcomings of KBE DCE model are discussed next. KBE DCE tool does not "predict" contribution to closing effort from pressure spike (air bind) in the cabin on closing door and adds pressure effect as fixed number. Typically, pressure spike (as per various contribution and teardown analyses) is 30-40%, making it an important factor to study and design. The requirement on pressure spike of closing door is not to exceed 300 Pa, compared to reality in 5.3 below.

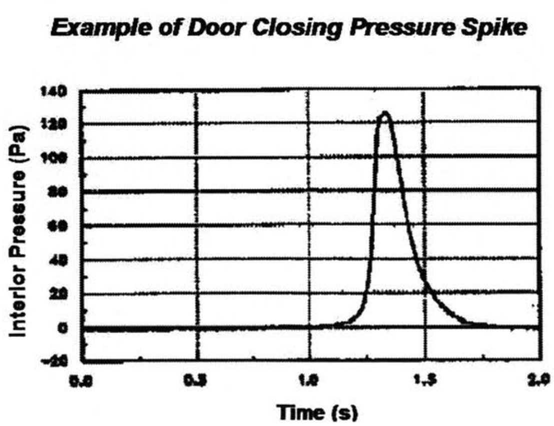


Figure 5.3: Air pressure spike upon closing door

Also, though the DCE modeler studies the effects of door variations in three discrete assembly positions (nominal, inboard, outboard) only. Moreover, the modeler needs more about latch-striker misalignment.

Figure 5.4 shows misalignment on one (production) door near 0 mm outboard; and this increases effort:

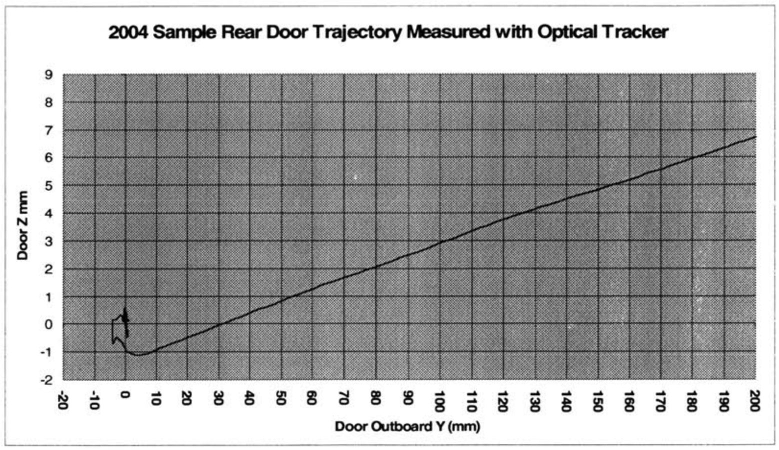


Figure 5.4: latch-striker misalignments mean the door has to be lifted in vertical direction

DCE modeler is used minimally on programs, and has not been well-correlated with physical test data, slowing improvements in it. The Modeler interface requires manual data entry. End users (system engineering staff) lack the time to implement the tool and using DCE tool is not a PD process milestone.

In addition, the current ownership with Technical Specialists, not PD closures team. There is a need of projects for KBE-based Adams DCE tool to improve the model's accuracy and completeness e.g. by including variation and pressure effect. It has been discovered that Toyota can accurately predict DCE with early program design.

Besides DCE there is also a KBE hinge band modeler that aids in setting the initial geometry for the door hinge positioning. There are several other tools used with varying consistency to manage technical complexity.

Following models (CAE) in figure 5.5 are available for use:

Department	Attribute	Requirement Title	Requirement Target	CAE Acceptance Criteria
Body CAE	Noise	STATIC STIFFNESS ATTRIBUTES	Program taget	>1.05*target (ACM model)
Body CAE	M&F/Noise	DOOR FRAME DEFLECTION DUE TO SEAL FORCES	Max Displ < 2.0 mm	Max Displ <1.7 mm
Body CAE	Efforts	DOOR SAG	1)Max Deflection < 38 mm TRIMMED ON VEHICLE; Gravity + 1000N load; 2)Max. Perm. Set < 3 mm TRIMMED ON VEHICLE	1)Max Deflection < 32.3mm TRIMMED ON VEHICLE; Gravity + 1000N load; 2)Max. Perm. Set < 2.55mm TRIMMED ON VEHICLE
Body CAE	Efforts	DOOR DROP-OFF	1)Max Deflection < 1.0 mm DOOR IN WHITE ON VEHICLE. 2)Max Deflection < 2.0 mm TRIMMED DOOR ON VEHICLE	1)Max Deflection < 0.85mm DOOR IN WHITE ON VEHICLE. 2)Max Deflection < 1.7mm TRIMMED DOOR ON VEHICLE
Body CAE	Noise	HIGH SPEED DOOR DEFORMATION FOR WINDOW NOISE	Max Displ < 2.5 mm for 100 mph at 20 deg yaw	Max Displ <2.13 mm for 100 mph at 20 deg yaw.
Body CAE	Noise	WINDOW FRAME LATERAL RIGIDITY	Max. Deflection < 5 mm. 2) Max permanent set < 1.5mm	Max. Deflection < 4.25mm. 2) Max permanent set < 1.3mm
Body CAE	Noise	DOOR TORSIONAL RIGIDITY	Deflection < 4 mm	Max. Deflection < 3.4mm

Figure 5.5: List of CAE tests and targets used for side door attributes

There is heavy reliance on physical testing, especially between prototype and launch stages.

Test methods for various PD stages

NA OEM tests all components and systems. On the other hand, Toyota tests to determine performance limits and then balances out the system. At NA OEM, following tests for door systems are carried out:

- Teardown Analyses for DCE: on prototypes, programs devise DOEs for special cases
- Pressure Measurement Gage: not high-resolution, 300Pa is actually greater than twice the pressure spike for good closing effort. Pressure spike test and requirement or not implemented
- Force-Velocity correlation: by closing the door from a 2-3 inch opening radius and using a velocity gauge, this measures the velocity targets for closing doors. At best it is a proxy for assembly plants to test what DCE customers find acceptable and usually under-predicts the minimum closing velocity. This is because NA OEM does not close doors from fully open radius
- Wind tunnel tests to assess noise performance and soak tests for water leaks
- Chucking and striker tests on rough road surfaces in proving grounds and tracks
- Collection of margin and flushness dimensions from optical readers in production

Importantly, figure 5.6 shows an energy loss at fully open position (that customers do experience):

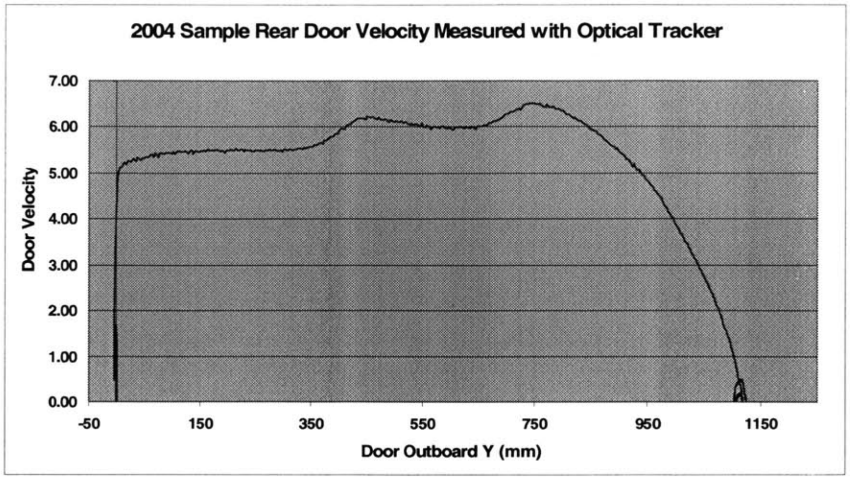


Figure 5.6: Door velocity versus opening radius

Note that the graph in figure 5.6 is unrelated to the force-velocity correlation test. The graph indicates sources of energy loss not captured by NA OEM's test method to find velocity: seal drag; friction in hinges; air between seals. The graph shows that losses at 300 mm outboard are missed by current force-velocity correlation method's insufficient opening angle, on which more studies should be conducted. At Toyota, a test that does not reflect customer experience would not be used at all. A greater amount of competitive benchmarking would also help improve system designs. Standardization would serve as a key lever for the PD team to manage technical complexity. Apart from proving these points through simulations, the next chapter covers insights gained by applying DSM tools.

6 Design Structure Matrix (DSM)

This chapter covers the core of this research: applying the design structure matrix (DSM) to NA OEM's closures development process for finding critical tasks and simulating the time evolution to test methods for improvements.

A technical and organizational tool

The DSM serves to document, study and approve the technical and organizational aspects of task-based processes, such as product development. Below in figure 6.1 is an example matrix:

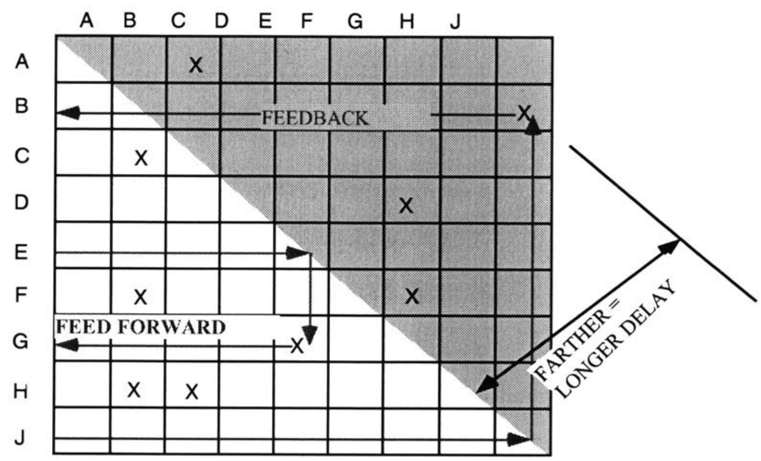


Figure 6.1: Sample DSM [Source: Whitney, 2006]

The list A – J comprises of design tasks or decisions in time sequence and x's indicate links between tasks as shown. One metric for process complexity is the number of marks per row. According to the above DSM task B needs information from Task J and task G needs info from Task E. The list and marks are developed by interviews and documents. The DSM-based model is used for sequencing, clustering (finding sets of closely related tasks that should determine organizational team structure), simulating, and optimizing design tasks for improvements in product cost, timing and quality.

Project Context, research methodology and approach

The first parts of the project to help improve closures system design dates back to 2003. The current DSM was built over the last two years to capture tasks that determine performance on door attributes. The idea was to help in PD improvement by focusing on design, management, and delivery of: closing effort, wind noise, water leakage, fit-finish, chucking. This DSM is also the first comprehensive closure PD documentation in this company. To develop this DSM, reviews of documentation, studies of NA OEM intranet and interviews with cross-functional engineers were conducted. Some of the goals were:

- Develop DSM and DFC for current process
- Capture Knowledge of Design Process for Attributes
- Simulate PD Process Time Evolution
- Gain Insights for Process Improvements
- Document of Physical Interfaces
- Survey System Integrators Job Details
- Use Design Structure Matrix (DSM) and Datum Flow Chain (DFC) to document organizational, design, and physical interfaces to improve closures design and manufacture

Simulation data such as task timing and probabilities of rework were also collected via interviews with design and release engineers as well as integrators on several programs (eight in total). Some of the expected results included convincing management to raise system focus and improving roles and responsibilities of Closures System Integrators.

Data collection: documentation and interviews

From June 2006 – April, 2007 the DSM of task-based inputs (design parameters, computer models, and physical tests) for system attributes was built. The research was started with design guides and validation documents. Eventually, as many as 40 people were interviewed for 4-5 times on average. The interviewees spanned the functional groups and sub-organizations of manufacturing, stamping, plant teams, product development and suppliers. Each interview lasted 1-2 hours and was mostly on the longer side. Given the resulting matrix, about 25 minutes in interview time per mark were invested. A summary of the DSM progression is as follows:

Information Source	Number of Inputs	Number of Marks per Inputs
Design Documents	23	3
D&R/Component Engineers	52	4.86
CSI-type Engineers/Supervisors	44	7.23
Cross Functional Engineers/Experts	82	9.18

Table 6.1: Progression of Knowledge Captured in Closures Design Structure Matrix

Through the process, following key observations were made:

- Most component knowledge is captured in documents (1/3rd of total DSM knowledge based on the division of interactions captured)
- Most system-level knowledge is in the minds of engineers (2/3rd of DSM)
- Longest interaction chains and largest clusters came from interviewing system-oriented engineers with experience (from attribute overlap analysis covered later)

DSM was validated by management or engineers as well as component or special task experts.

Validation and improvement steps

At each of the significant milestones, the DSM was reviewed and validated by various stakeholders. After the first version (based on documents only), design and release engineers for components included as DSM tasks stated the need to include interfacing tasks and components. After these engineers were interviewed and their experiences documented in task list and interactions, system-level engineers validated the DSM and helped expand it. This work was carried out mostly in the product development cluster. However, with the help of the system integrators (CSIs) in closures, it was decided to include the critical tasks and interfaces outside of PD that affect the performance of the process for attribute delivery.

Consequently, plant teams, manufacturing engineers/integrators, stamping experts and supplier engineers were interviewed. Despite these improvements the following limitations are acknowledged:

- Most data are from car programs (vs. truck and others)
- Sample includes up till 2009 models (vs. latest kick offs)
- No direct interviews from the Studio (concept design) team
- Domain knowledge needed for deep insights
- DSM from best-in-class OEMs such as Toyota unavailable

Though the findings represent the opinion of MIT's research team, main results have been sanity-checked with CSIs. Once the DSM is obtained, several analyses were done for insights.

Discussion of Resulting DSM

The DSM developed contains PD tasks that revolve around design parameters, cross-functional design decisions such as assembly and locator schemes (with manufacturing), sheet metal formability (with stamping), physical testing of product performance (with prototype facilities) and measurement of assembly capability (with plant teams). The following captures the structure of the resulting DSM:

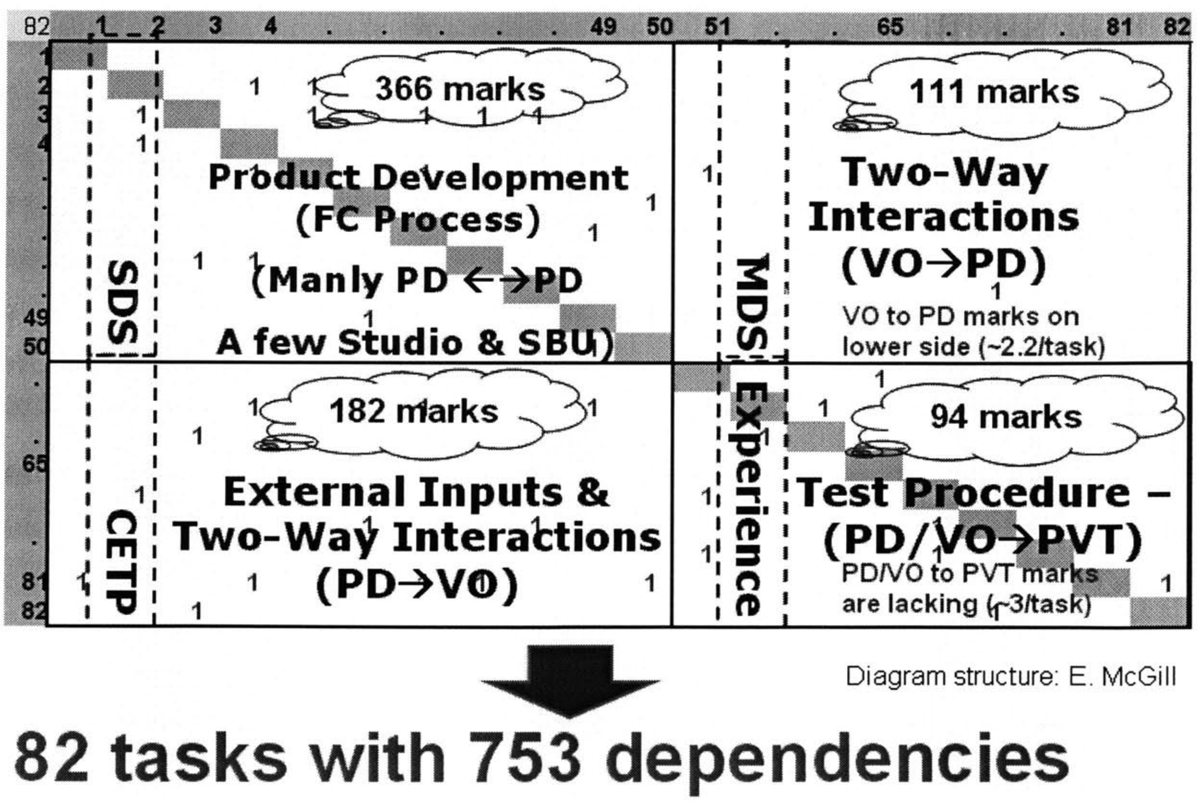


Figure 6.2: Structure of the Closures PD DSM for Attributes

The DSM has a 'marks per task value' of 9.18 on average. System design guides drive PD tasks, Manufacturing Design Specifications (MDS) guide manufacturing tasks and corporate engineering test procedures (CETP) guide physical testing. A significant portion of work is done from experience. Several insights, both technical and organizational are drawn.

Technical insights

Typical process-based DSMs have a mark density of 6 per task on average. Closures process is a highly complex and coupled one based on 9.18 marks per task. The following were observed through the DSM:

- Several iteration loops (non-sequential information flow or feedback)
- Several conflicting decisions (attribute conflict through design parameters)
- Several tasks exceed prescribed process time making PD difficult to complete on schedule

Also, it was discovered that it is not possible to re-sequence order of tasks and that the current sequence (as-is) reflects the best possible one. This is different from the one possible outcome of DSM analysis, where tasks are re-sequenced through optimization to minimize the above diagonal marks (feedback).

However, it is not too surprising because NA OEM has an optimal sequence already due to experience gained over several decades. In young processes or companies, it might be possible to help improve task sequencing to minimize feedback.

The more experienced a process and its executioners, the more likely it is that they have homed in on the appropriate task order. However, this does not solve the challenge of managing attribute conflict or prioritizing the right type of work (e.g. modeling versus testing).

The diagram below captures some of the attribute overlap analysis performed using the DSM.

For the diagram below in figure 6.3,  symbolizes an iteration loop, while → shows the direction of design information flow. Such overlap analysis points out important loops to manage and the design parameters that cause attribute conflict, such as sealing.

System engineers and integrators can base their decisions and make a case to management for more attention to attribute balancing by using the information already contained in the DSM developed over two years. Figure 6.3 shows a representation that is extracted from the DSM:

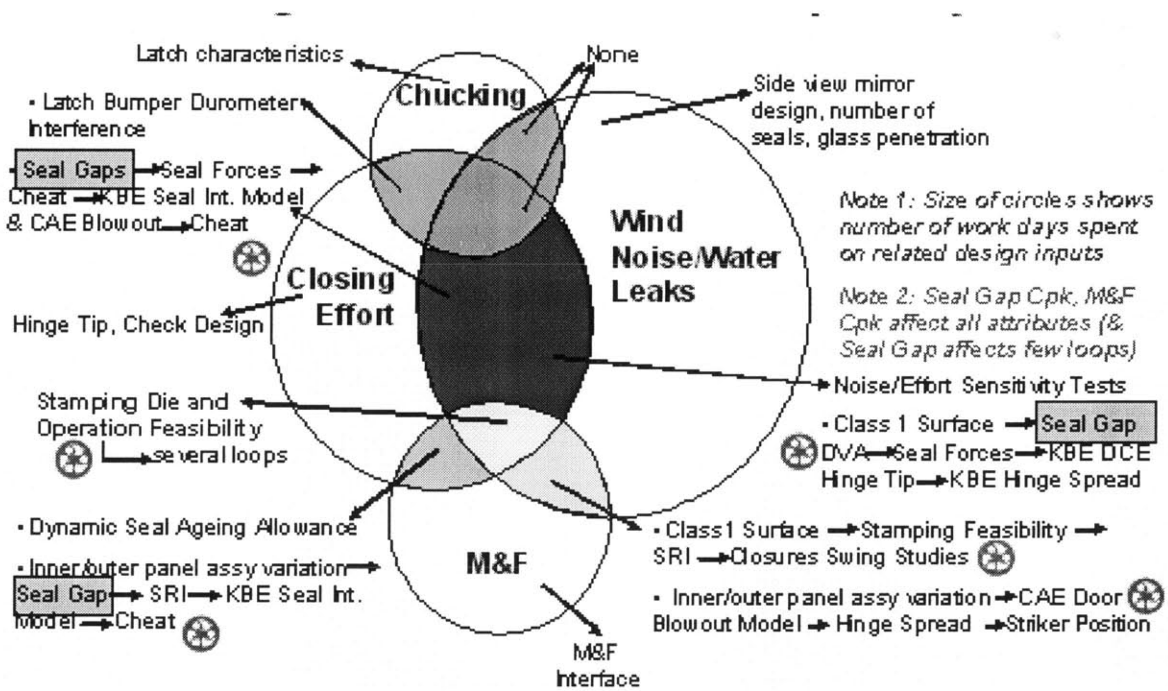
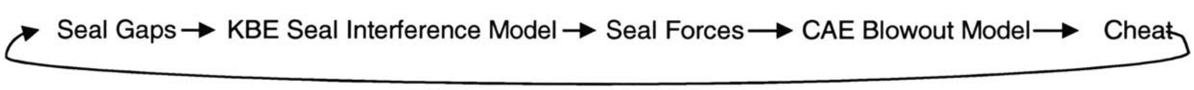


Figure 6.3: Findings from the DSM – attribute overlap analysis

Following is an example of Noise and Effort overlap loop:



For above loop, input-attribute relationships are:

- Cheat and blowout → wind noise is affected the most by these decisions
- Seal gap and force → effort is affected the most by decisions on sealing
- KBE Seal Int. Modeler → both attributes are affected due to the tradeoff

The design parameter overlap for attribute leads to technical complexity. As highlighted, seal gaps or other parameters appear in several design loops that affect individual attributes. As such, these loops and the attributes themselves are inter-dependent, and several tradeoff decisions have to be made. For instance, tighter seals help wind noise (as seen in the noise loop in figure 3 whereby the amount of blowout would reduce) but deteriorate closing effort at the same time. Therefore, decisions have to be made to strike a reasonable compromise in sealing parameters to balance the attributes. Several other rework loops and attribute overlaps could be traced using the

DSM for a PD process. From observations at NA OEM, it is found that best practices in knowledge and attribute management are not always followed. For instance there is imbalance in system decisions and prioritization, where wind noise is usually given preferential treatment over closing effort (more on this later). The DSM shows effect of changes and late interventions that can affect the success of a PD process.

Organizational insights

The as-is DSM cannot be clustered into smaller sub-groups that would correspond to teams in an organization. Usually, this and re-sequencing the task order to optimize decision-making for reduced number of iterations is the most direct outcome. The fact that clustering is not seen implies a highly coupled process. For the organizational aspects, the following setup in table 6.2 adds to attribute interface complexity in the organizational sense:

	Control All	Control Part
Own All	Water leakage Blowout Hinge and latch	Closing effort
Own Part		NVH

Table 6.2: Organizational Complexity of Attribute Interfaces [Source: Whitney, 2007]

For definitions above: "Own" = responsible for delivery and "Control" = can make influential design decisions. The fact that attribute-related tasks or decisions are owned and controlled by different groups at different levels adds to the challenge of attribute delivery for the system. Moreover, information is exchanged between several cross-functional teams working on their specialized tasks in the PD process. In addition, the process interface analysis shows a high number of handoffs within and between several design, assembly or manufacturing clusters. This implies that some of the iterations or rework are created due to loss of information, which then has to be recreated partially and in some cases, even fully.

This calls for a conscientious effort to coordinate such information exchange for DSM tasks. The role of simultaneous engineering (such as Toyota's Production Engineering Cluster – PE) or a system-level engineer (such as NA OEM's Closures System Integrator – CSI) is covered in upcoming chapters.

Process simulations

Simulations help discover and confirm levers for process improvement, based on figure 6.4:

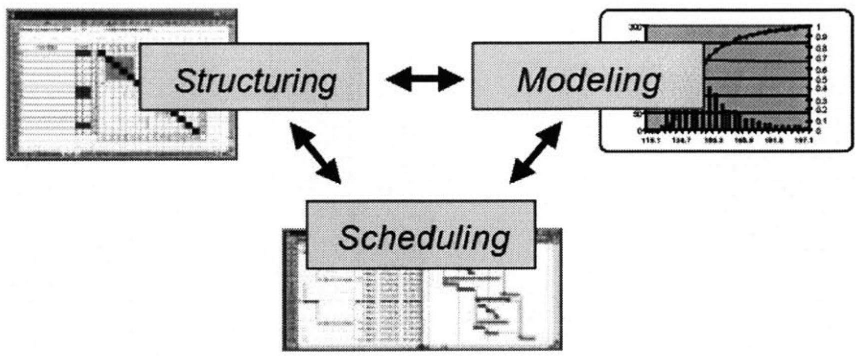


Figure 6.4: Process simulations using DSM and relevant data [Source: Cho, 2003]

An as-is DSM can sometimes be restructured using a partitioning algorithm that minimizes the number of above-diagonal interactions to ensure an optimal sequence of task with maximum possible feed-forward information flow. The idea is to reduce information feedback to earlier tasks that would cause rework through iteration loops. As discussed already for the PD DSM in closures, structuring the DSM for better sequences of task execution is not possible. However, simulations lead to several results using:

- DSM-based task interactions to determine inter-dependencies
- Task durations drawn from triangular distribution: mean, worst best estimates (interviews)
- Resources (engineering manpower) available and required for the tasks
- Other data used probability of rework, learning effect of each task , likelihood of changes

The DSM was simulated using Matlab code written by Eric McGill [McGill, 2005]. Please see Appendix 1 for the exact code used, in Matlab script. This code builds on code in Excel macros available at http://www.dsmweb.org/. This simulation combines data on once-through task times and rework probabilities to obtain an estimate for the time to do all the tasks listed in the matrix, including rework. Each run of the simulation draws task times and rework events from probability distributions generated from interviews with closure design participants. The simulation is run 1000 times and the different total completion times are accumulated in a histogram. In the simulation module used, tasks work in parallel with upstream precedents when possible. The simulation results are only as good as the task durations, probability and learning curve data that are used as inputs. The results of DSM simulations for this project were validated by CSIs and other engineers: if they completed all tasks and rework loops created by the structure of the as-is PD process, they would take at least three times longer than what is allowed by process milestones. [NA OEM Interviews, 2007] Also, durations data from independent programs were found to be in good agreement (in terms of task duration ranges) with each other. Simulating the as-is DSM, the following process completion times in figure 6.5 are obtained:

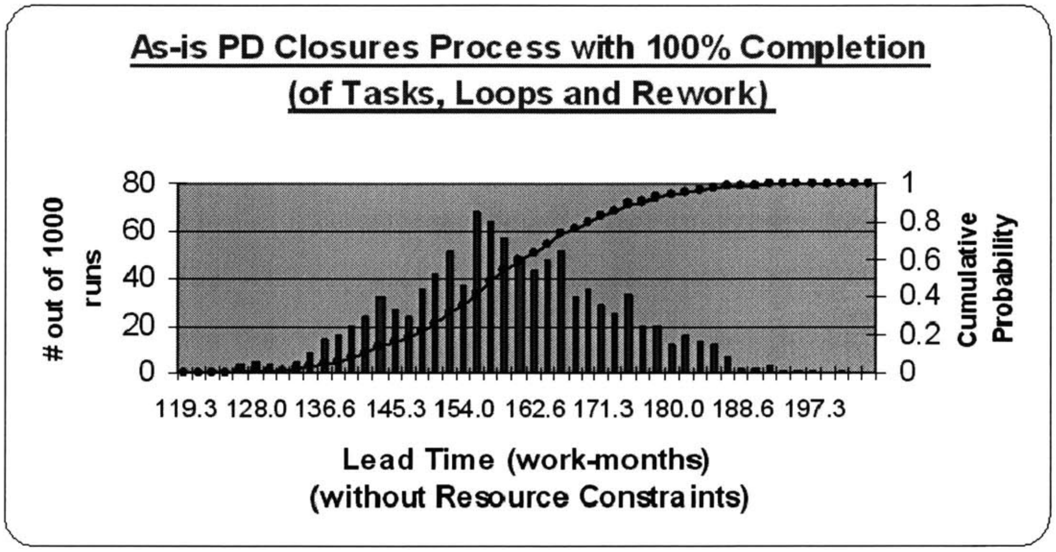


Figure 6.5: Process timing if all tasks are completed as per the current PD process

It is to be noted that the process is supposed to finish in 50 work-months (or about 1000 work-days) or less, as per the timing prescribed by NA OEM. Without resource constraints, the current process would take an average of 151 work-months with a standard deviation of 12 work-months. With resource constraints (that is using only the currently available NA OEM resources) the timing increases to an average of 177 work-months with the same standard deviation. Therefore, even with infinite resources, an all-new vehicle's design process would exceed program timeline indicating the high complexity from task interactions captured in the DSM. The coupled DSM means tasks repeat. It is important to interpret simulation results. 50-month programs have doors but they are not as good as they could be because:

a. Tasks are not given the time they need
b. Interactions that should be checked are not being checked
c. Time is spent elsewhere that is not accounted for here, such as fire-fighting during launch

Moreover, for execution of PD tasks, the process is beyond the tipping point (discussed in point number 8 on previous page) with resource utilization of *81.4% on average and 121% for maximum* in worst case.

Using a tearing algorithm could improve the situation. Tearing leads to taking out marks to open up loops and declaring these marks as outputs. Practically, tearing the DSM implies standardizing. Applying the algorithm to the as-is DSM, tearing identifies the following tasks as high-impact for process decoupling and opening of rework loops (code in Appendix 1):

- Platform assumptions
- Stamping die and operation feasibility
- Number of seal walls (use standard strategy) and Seal Gaps (use standard parameters)
- Door Cheat (standardize, e.g. stiff header, no cheat)
- Door Closing Efforts Test (use KBE Modeler instead)

Simulations after tearing these tasks show a result of an average process timing of 143 work-months (117 with infinite resources) with a standard deviation of 12 work-months for both cases. There is still a need to identify more time reduction ideas. The following are explored:

1. Assessing impact of extra resource allocations (discussed above)
2. From experience, certain other tasks can also be 'torn' out, such as common parts
3. Better prediction tools for tradeoffs (comprise 23% of DSM interactions e.g. Seal Forces)
4. Benchmarking and better knowledge management (25% head start on times on average)

Based on program experience and observations, the following tasks could also be 'torn':

- Side view mirror design (external to Closures)
- Assembly schemes & variations (plants known)
- Hardware: latch, hinge, check, bumpers (tests)
- Effort-noise sensitivity test (model using DFC)
- Dynamic Seal: margin/rocker, drag, ageing, dimensional variation studies
- Static Sealing: Extractors, Glass penetration
- Physical testing: almost zero reliance for design

This is a realistic possibility of process improvement because other OEMs (e.g. Toyota) can accomplish this. Using the simulations, the resulting process then converges to process timing with an average of 85 months (vs. ~50 in process milestones) and a standard deviation of 9 months. With the improved process, assigning infinite resources improves lead-time by << 1%. Consequently the process approaches a lean frontier, whereby there are no excess resources as waste and no significant incremental benefit from adding resources. Knowledge improvement (learning curve) is critical in converging with timing as well because this enables the reuse of existing knowledge from special studies or program experience to cut down on average task times. The benefit of implementing these ideas was tested with the DSM and simulation tools. If these ideas show benefits (which is indeed the case) for process timing and product timing, NA OEM would make a good investment. The following shows results of simulations after all the proposed changes for process enhancement are applied to task times and structure of the DSM:

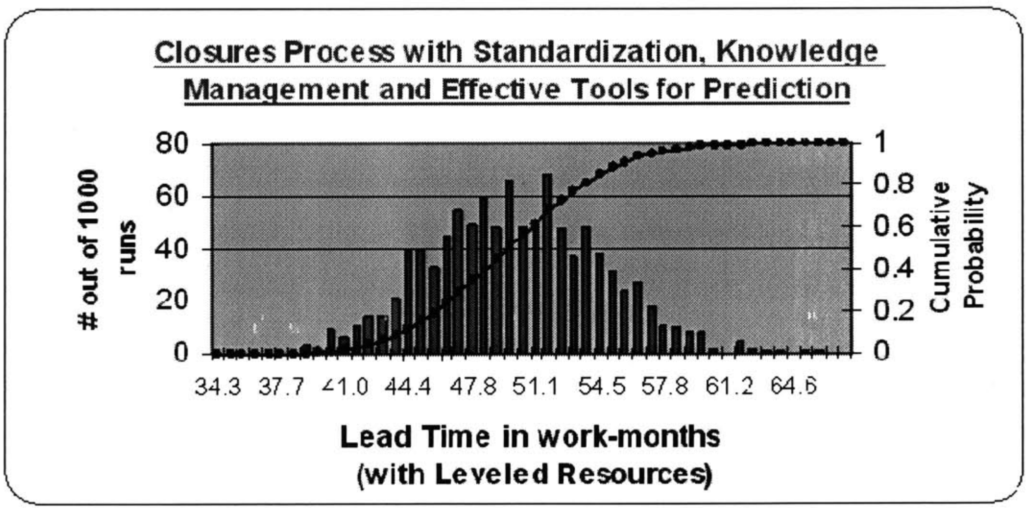


Figure 6.6: Balanced process with all possible enhancements from DSM-driven levers

In the distribution below, the cumulative probabilities of completion are as follows: Mean distribution (10%, 30%, 50%, 70%, 90%) = (44.2, 47.2, 49.7, 52.2, 55.6) months. Above result is largely compliant with both process timing and system design needs. The average lead-time is 49.8 months with a standard deviation of 4.7 months for all tasks and loops to be completed 100%, ensuring higher product quality. This is possible with a front-loaded process and better resource utilization below the tipping point. With all possible improvements, resource utilization drops down to 64% on average and 99% in worst case scenario of rework. This means that the system is in stable equilibrium. Improvements to the PD process are summarized in the diagram in figure 6.7 on the next page, with the as-is process on the left-most part and the balanced process (with all suggestions for improvements implemented) on the right corner:

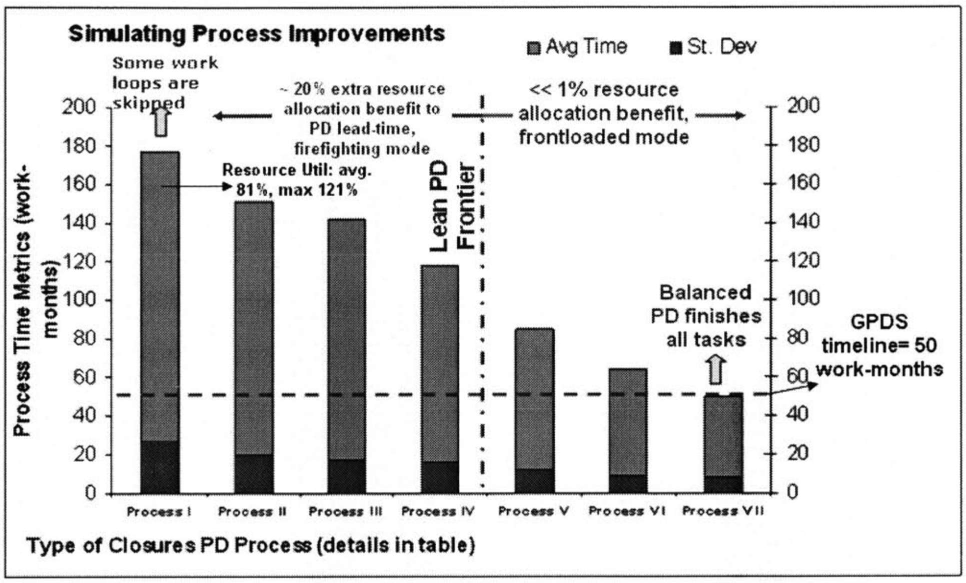


Figure 6.7: summary of enhancements possible to PD process and timing impact

The above diagram presents a summary of how each enhancement to the PD process affects process timing. Basically, we have proven that applying the suggestions from this research would enable NA OEM to not only meet its process timing but also enhance the quality of the product by completing all tasks, system considerations and rework loops that arise from revisions.

The following table 6.3 is a key to what changes are made from one process to the next

:

Axis Title	Process Key
Process I	Current PD (with actual resources in the as-is state)
Process II	Current PD (with infinite resources in the as-is state)
Process III	PD with Prioritized Standardization (tearing, actual resources)
Process IV	PD with Prioritized Standardization (tearing, infinite resources)
Process V	PD with Complete Standardization (tearing + other bottlenecks)
Process VI	Standardized PD (from V) with Knowledge Management
Process VII	Standardized PD w/ Knowledge Mgmt (VII)+Tradeoff Tools

Table 6.3: Definition of each process showed in figure 7

Based on the simulation results and categorization of tasks into five types, following is a comparison of how the resources are utilized (with respect to tasks) in the as-is versus the balanced process (predicted):

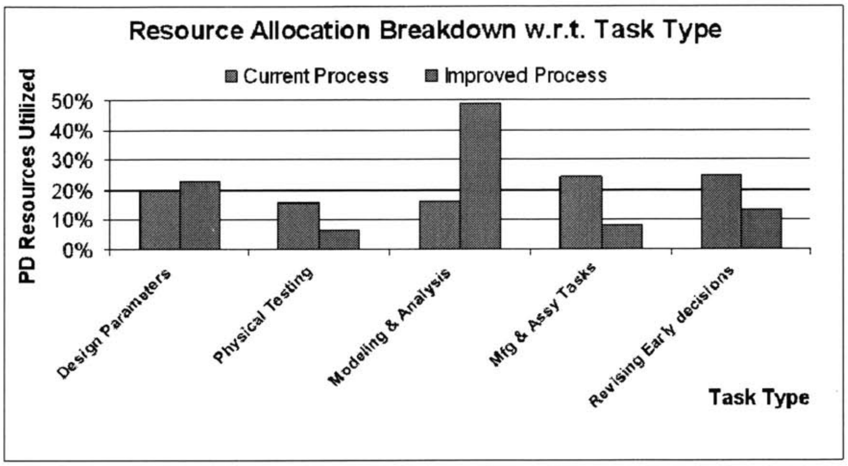


Figure 6.8: Breakdown of resource use for task-types in as-is and improved process

From comparisons of before and after resource usage on task types in figure 6.8, following are inferred:

- Increase modeling and analysis by three-fold
- Decrease dependence on physical testing by more then 50%

NA OEM should target the resource utilization as suggested by the improved process above.

Bottlenecks, resources and prioritization

It is possible to identify the bottlenecks, impact of changes to resources available and prioritization of tasks. A set of definitions starting with critical inputs to DSM tasks follow starting with figure 6.9:

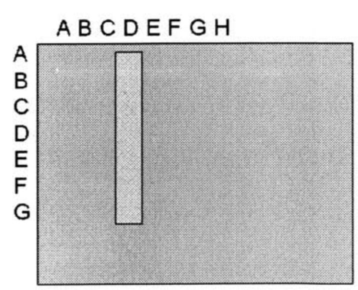


Figure 6.9: Definition of critical inputs or tasks [Source: Whitney, 2007]

The vertical, yellow strip above denotes presence of marks. Lots of tasks await input from task D. If task D is redone, many other tasks must be redone. Therefore, task D is a highly critical input to other DSM tasks and affects the success of this process. Following results were obtained in closures as-is PD DSM:

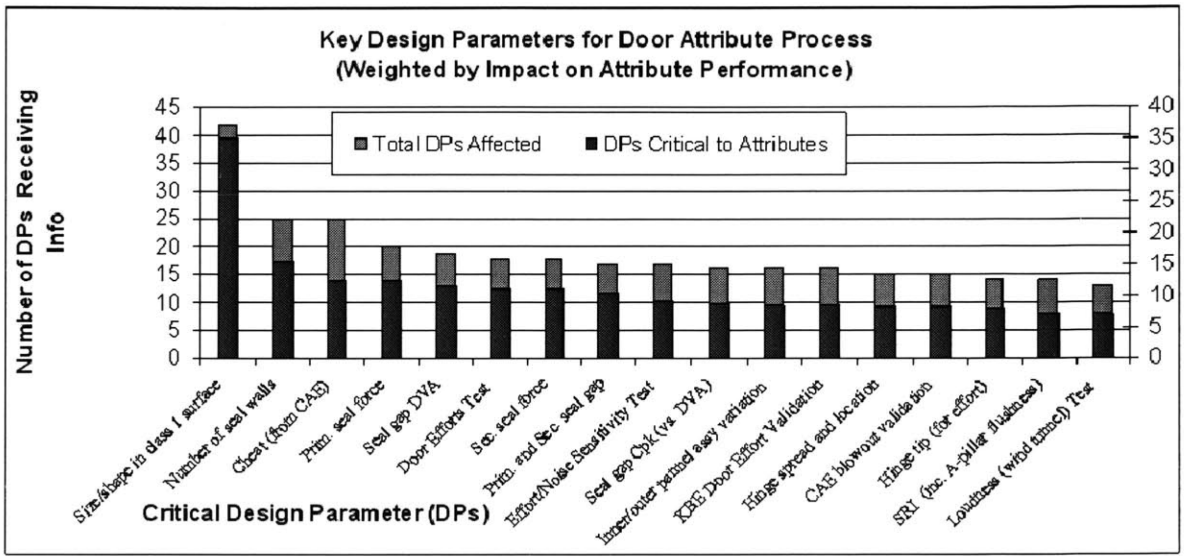


Figure 6.10: Critical Design Parameters that feed information to other tasks

From the figure 6.10, several inputs are critical, with these at the top of the list: class1 surface, level of seals, Cheat, Seal Parameters/dimensional variation studies, Tests (Effort and Noise).

Basically, it is intuitive to say that standardizing these inputs as much as possible would reduce the amount of rework arising from iteration loops and improve product predictability. It is not surprising that the most of the same inputs are identified by the tearing algorithm. The above results are weighted by the impact of each task on system attributes. Criticality analysis above and overlap analyses in figure 3 are consistent in identifying some of the same important tasks. Also, inputs with highest information outflow also have most impact on attribute performance (blue and red bars in the histogram have the same descending order). Notably, the studio surface is most critical – it affects 42 other inputs – and defines PD success to a great extent. Therefore, changes to this input should be avoided after data freeze. 50% of inputs receiving information from class 1 surface form process bottlenecks, as discussed next.

Also to be noted is the fact that given the above standalone findings from DSM, it is not surprising that the tearing algorithm has identified most of the same tasks or design inputs providing process benefits from standardization. Following is a definition of an information-based bottleneck in figure 6.11:

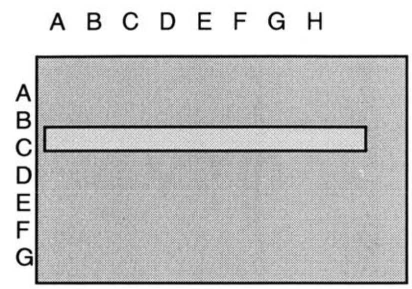


Figure 6.11: Definition of information bottleneck [Source: Whitney, 2007]

Task E depends on completion of many tasks and is an information bottleneck. The result for information bottleneck analysis (by counting marks in rows) is as follows: (The results below in figure 6.12 are weighted for attribute sensitivity (of change) from each task)

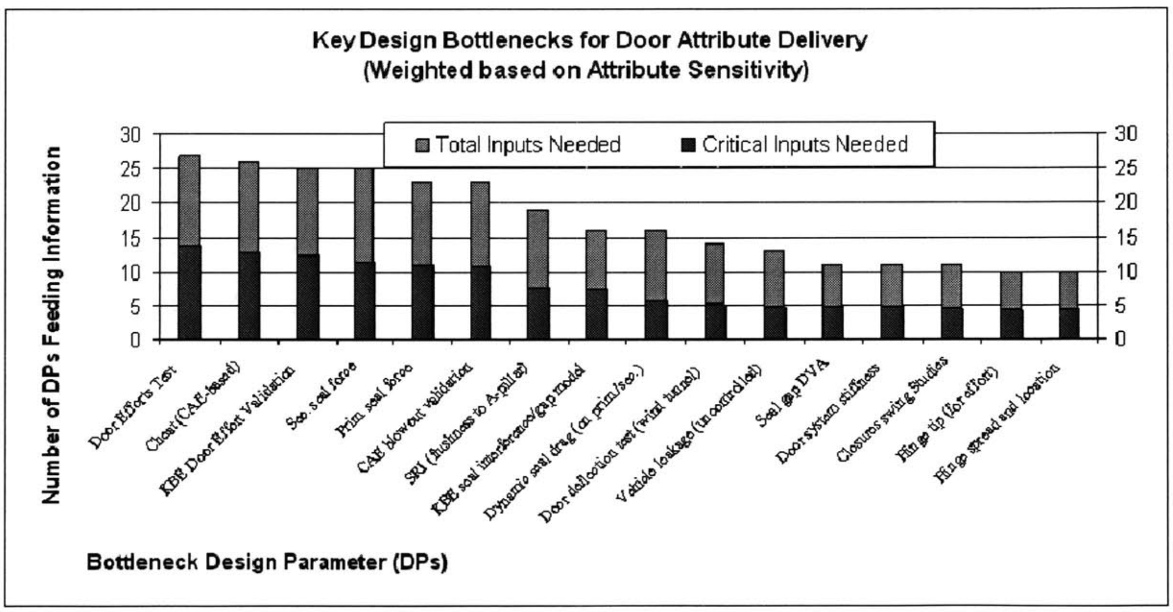


Figure 6.12: Information bottlenecks from DSM-based analysis

Bottlenecks are identified as: Efforts test, KBE DCE tool, Cheat and CAE tool, Seal Parameter, SRI and Seal Gap dimensional variation study. Basically, advance resource and task execution planning is needed for these tasks; otherwise the process completion is delayed. The insights include the fact that SRI, dimensional variation studies, KBE delay critical decisions and lead to rework and firefighting for PD. Also, door closing effort teardown test needs 27 (30% of all) inputs. Dependence on this physical test at the prototype stage to determine performance on closing effort should consequently be avoided. The fact that decisions on closing effort are finished after prototype build automatically create a rework loop feeding back into earlier decisions. Incidentally, the analytical (KBE) tool to predict closing effort is also a major information bottleneck because it depends on a high number of inputs to have been frozen in the design stage. The analysis confirms that Margin/Rocker Seal Forces are less important for attribute performance. Also, secondary seal force is tweaked till later than primary seal force, while ideally the decisions would be made in tandem.

Another definition of bottleneck tasks is based on task timing as per the simulation: bottlenecks of process timing are found based on times from simulations using program data (time-based bottleneck does not have enough time to finish as per process milestones and causes delay to the overall process). Following is the resulting set of tasks identified in figure 6.13:

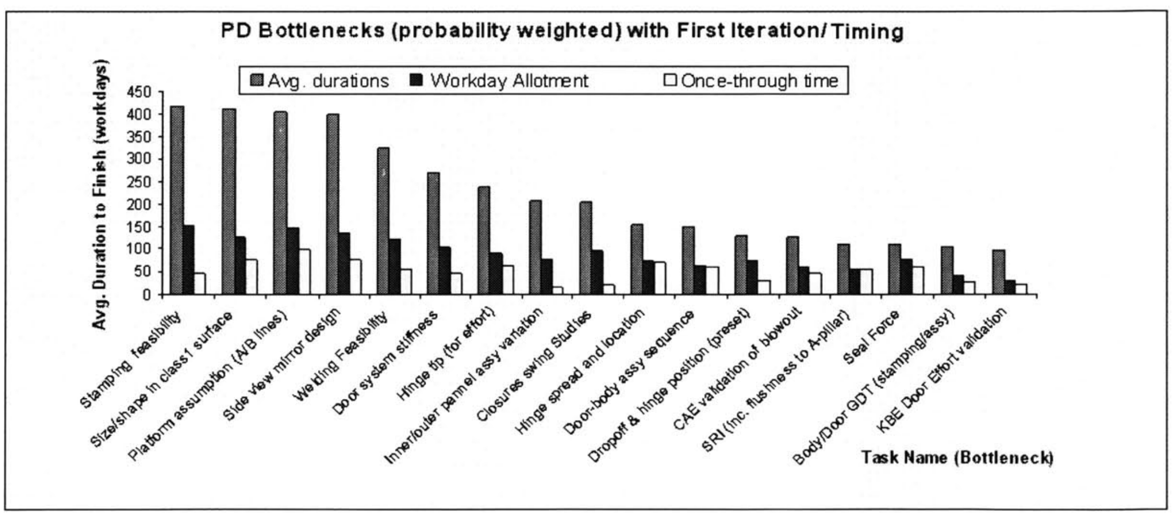


Figure 6.13: Identification of bottlenecks for process timing

Most early decisions form process bottlenecks, which puts the whole program at risk. The bottlenecks (tasks that cause difficulty in finishing the process are: Stamping/weld feasibility, studio surface, platform assumption, door stiffness and most assembly-related tasks. Times shown include all rework loops. The difference between timing required to complete all work on a task (as per simulation) and timing required by program milestones comes from the structure of the process. The improvements suggested for a balanced PD process would make the completion of all work within the prescribed 50 work-months more likely. The DSM also helps identify knowledge management and change needs.

DSM uses: knowledge and change management

Some of the key levers for low process timing at Toyota include standardizing and managing knowledge through documentation. However, review of 80 system design guides for 50% of DSM's PD-based tasks (DPs) gives the following breakdown of the type and availability of design knowledge in figure 6.14:

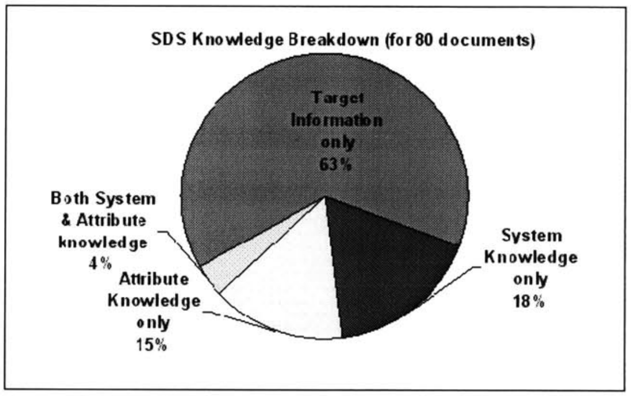


Figure 6.14: Type of design knowledge in system design specifications and guides

At least 10 design parameters (DPs) have no guides and some guides are redundant or based on insufficient samples. Such documentation or the lack thereof leads to rework. Simulations show better knowledge management helps reduce task times by up to 25%. According to observations, following are some causes of high timing while managing any PD process, such as that at NA OEM:

1. Hand-offs: Whenever responsibility for the product is handed from one group or person to another there is a hand-off. Each time there is a hand off significant information and time is lost. High numbers of hand offs also make it very difficult to build accountability into the system.
2. External quality reinforcement: Whenever a separate group is responsible for quality it takes ownership away from the primary person/group and adds significant waiting time for inspection
3. Waiting: The waste of waiting is rampant in product development. Waiting for data, a decision a resource, or for other parts to complete. This is a major source of queues and long lead times.

4. Transaction waste: This waste occurs when non-value added steps are required to accomplish the primary task. Bidding multiple suppliers, bringing suppliers on too late in the process, long statements of work, and long negotiations are all part of this category.
5. Re-invention waste: This occurs when the same problems must be solved repeatedly or when existing solutions (designs etc.) are not utilized. This is caused by a lack of learning.
6. Lack of system discipline: This is also rampant in some PD systems. The lack of scheduling discipline for instance causes arrival variation, which is responsible for long queues.
7. High process and arrival variation: Task (process) and arrival variation are two of the three primary contributors to long queues and lead times.
8. System over utilization: This is the third contributor. Once the system has passed 80% utilization very small changes in utilization have a dramatic effect on though put times [Reppening, 2000]
9. Large batch sizes: According to *Factory Physics*, generally speaking cycle times increase with batch sizes. Batch data releases are the primary culprit in PD waste. [Hopp & Spearman, 2000]
10. Redundant tasks: are tasks repeated across functions. Multiple inspection points are an examples
11. Stop and go tasks: Each time an engineer has to reorient for a task it is like a set up. When an engineer must restart a project several times it requires multiple "set ups".
12. Unsynchronized concurrent tasks: One of the most insidious wastes. It seems like the right thing to do, but unsynchronized concurrency is often the root cause lots of waste. [Morgan, 2004]

Some of the above (e.g. 3, 5, 7, 8) are found in the DSM and simulation analyses as well. We now look an operations management tool that can be applied to a given process to gain insights.

System Network Analysis

Much like the traditional DSM analysis that helps re-sequence a set of tasks to reduce reverse information flow or identifies clusters on which teams should be based; system network analysis fails to show any meaningful clustering. For instance, applying the Newman-Girvan algorithm renders 17 clusters among a set of 82 tasks and a clustering coefficient of only 0.056 (as expected in a highly coupled adjacency matrix – the transpose of the DSM). Figure 6.15 is one view of the system network:

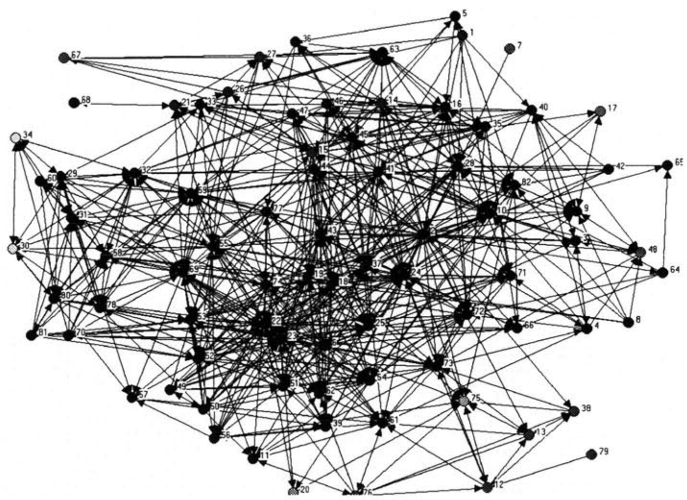


Figure 6.15: Network diagram of tasks in DSM (no meaningful clustering) [UCINET]

Basically, tasks cannot be ordered into clusters whereby the 'nodes' (tasks on DSM) within are more closely related to each other than with nodes in other clusters. In the context of PD processes, this points to the need of coordination between nodes that are assigned to different functional teams but essentially link with many other nodes in a coupled process. Insights gained from the DFC and flow down analyses are more complete and meaningful.

In conclusion, models based on DSMs provide insights. The next chapter discusses applications of Datum Flow Chain.

7. Datum Flow Chain (DFC)

This chapter covers datum flow chains and other methods of studying design operations, such as Network Analysis and Axiomatic Design. Also included are conclusions and insights for interface management, both physical and organizational, are drawn from these methods.

Fundamentals of Side Door Construction

After all the design-based tasks are completed to satisfactorily deliver attributes, fabricating a door and attaching it on the car body has two remaining parts after the product launch stage, outlined as follows.

Stamping

This entails forming of sheets of metal (commonly called sheet metal) into the inner and outer door shells, called door panels (as described earlier). At NA OEM, the stamping sub-organization falls under the manufacturing organization, with its own director and resources. NA OEMs owns stamping plants that serve some of its vehicle programs, but most of the stamped doors come from suppliers on many programs. Surprisingly, coordination seems equally challenging between in-house and external suppliers.

Assembly

The door contains many components. Internally, there are mechanisms such the window regulators. Though critical, such component assembly does not directly affect the understudy attributes. For the case study, assembly begins with hinge mounting. The DSM already contains all the design-related tasks that would determine dimensional performance on hinge mounting. The following notes are relevant:

1. A fixture is used to place the door outer with respect to door inner in up-down and fore-aft during the hemming process in door construction
2. For the program studied most closely at NA OEM, door construction takes place in the body shop of same assembly plant (includes setting hinge tapping plates).

3. After initial hinge mounting and door hanging process, the doors and body in white (BIW) go through paint. Then the doors come off for trim (meaning final assembly), then back on again.

For the second major step, the door is assembled (hanging process) to the car body. Because NA OEM owns several assembly plants, the exact details would change depending on the equipment available at the plant and such. Details of assembly and constraint can be captured in a datum flow chain (DFC)

Key characteristics for side door attributes:

A Key Characteristic is a feature of the sub-assembly, part or process whose variation from nominal impacts the final cost, performance, customer's perception of quality, or safety of a product. For doors, seal gaps, margin and flushness are all KCs.

Attribute Flow down

The following process flow affects seal gap dimension: receive door; put door in fixture; apply fixture to cab, (manually adjust door flushness), paint, remove door, receive striker, put striker in fixture, apply striker to cab, (assemble components on door*), re-apply door, (manually adjust door flushness). The steps in brackets are those controlled manually. The * is to note that once door is off, its components are put together in simultaneity with putting the striker on body (cab) without doors.

The door is clamped on a fixture at four points. The fixture is then brought to the vehicle where a second set of clamps attaches four different points on the fixture to the body. Bolts are driven to attach the door to body, and the fixture is removed. A door fitter attaches a weight inside the door to replicate trim mass, and adjusts hinges to make the door flush with the B-pillar and roof. This allows access to parts of the fender assembly that are inaccessible later on. The door is taken off after paint, and then reattached. At the very end, doors are re-examined by fitters for necessary readjustments. It has been found that NA OEM does not account for fitter actions in any assembly modeling, but this is most likely the case across all OEMs although fitters are utilized-industry wide. [Leland, 1997].

The following diagram in figure 7.1 shows the flow down to cascade attributes to components:

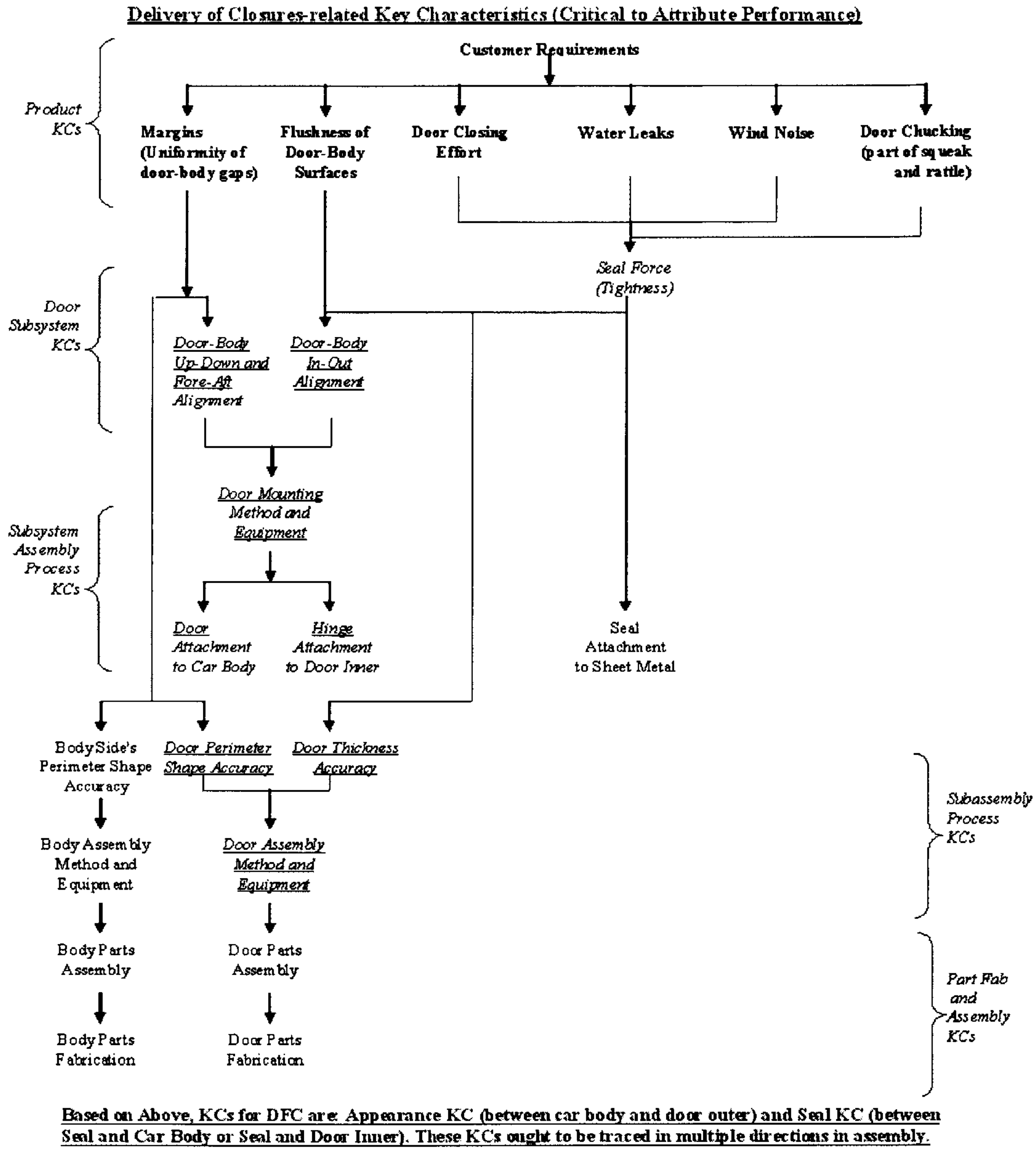


Figure 7.1: Delivery of Door KCs – Flow down

KC Flow Down

As discussed in early chapters, door closing effort is directly related to seal gap. Seal gap is related to door flushness to the B-pillar. Door flushness is affected by various processes including door apply (with cab deviation at roof and floor, fixture shims at roof and floor, location of front fender), striker location (B-pillar outer flange, shims in fixture to body, striker location in fixture, shims in fixture to striker), latch location (location holes on door), quarter panel location. The above sequence can be used to quantitatively predict how the seal gap dimension will vary based on variation in its component parts. There are two parts of analyzing the flow down: mean location and variation contributions. This is used in design verifications. The KC flow down during the development phase is critical to ensure that the right characteristics are chosen. It is far from trivial to complete KC flow down for the seal gap dimension in final assembly. Some of the reasons for this included the complexity of running VSA and seal gap models, the importance of other dimensional directions (fore-aft, up-down) and the need for grasping continuous seal gap as opposed to certain pre-selected points.

Assembly considerations for PD stage

Components that are *italicized* affect attributes: *Door inner* and *outer panel, Hinges, Primary and Secondary seal, Check,* Window glass, Latch system (latch casing, pawl, spring), *Margin seal, Rocker seal, Over-slam bumper, Body-side structure,* Glass runs and seals, Trim and mechanisms, *Striker.* In a successful product delivery chain, manufacturing and assembly considerations would be closely coordinated with all design decisions starting as early as possible. The DSM contains assembly-related tasks and decisions from PD. However, other tasks also affect product timing and rework in launch.

Assembly inputs to design: current vs. missing

The decisions on locator schemes, variation stack-up allowances and assembly capability are included in the DSM. However, the ergonomics and line-balancing aspects are not. Though beyond the scope of this case study, it is worth mentioning that engineers on launch end up spending a significant time in solving these 'other' assembly issues. A better coordination between design and manufacturing to address these issues would improve the process, focus on knowledge transfer to plant team and tweaking for attributes.

Datum Flow Chain (DFC)

Following is a definition and example of a DFC:

Datum Flow Chain (DFC): subset of liaison diagram with part names in the chain, identifying assembly features and constraint relationships as plans for achievement of KCs. It is derived from the liaison diagram, whereby directions are assigned to liaisons (links) to indicate one part has the responsibility of locating another part, and defining constraint. Constrained degrees of freedom (six total: linear x, y, z; and three rotations thereabouts) are written with DFC links. Figure 7.2 is a simplified Chain for a door:

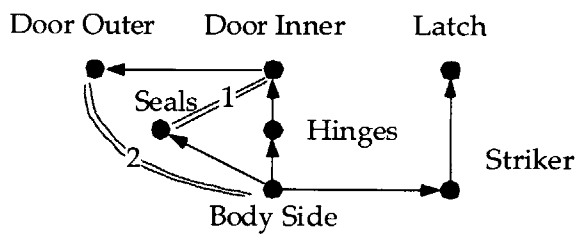


Figure 7.2: Example DFC [Source: Whitney, 2004]

Figure 7.2 documents part relationships that define attributes: 1 = closing effort and leakage; 2 = fit and finish. It also allows design of schemes to achieve tolerance. Following information on types of assembly relationships is encapsulated in a DFC:

Contacts – These are joints that support and fasten the part once located, with no effect on constraint.

Mates – joints that constrain and give dimensional relationships between parts (with assembly features)

Liaison Diagram – This shows where parts in an assembly join with each other. It is a simple graph that encapsulates connectivity information using nodes to represent parts and lines between nodes to represent liaisons or connections between parts (as done for the example of side doors).

Symbols in a Liaison Diagram or Datum Flow Chain (DFC)

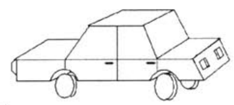
=== Key Characteristic (KC) ___ Mate ---- Contact

⟶ Delivery of Constraint and Dimension through a Mate

---▸ Hybrid of Mate and Contact delivering Constraint and Dimension depending on Direction

⬭ Sub-system or component comprising of more than one part

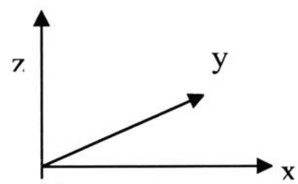
Assembled Door Liaison Diagram – the following are some definitions of axes and terminology:



In—Out: y—axis

Fore—Aft: x—axis

Up—Down: z—axis



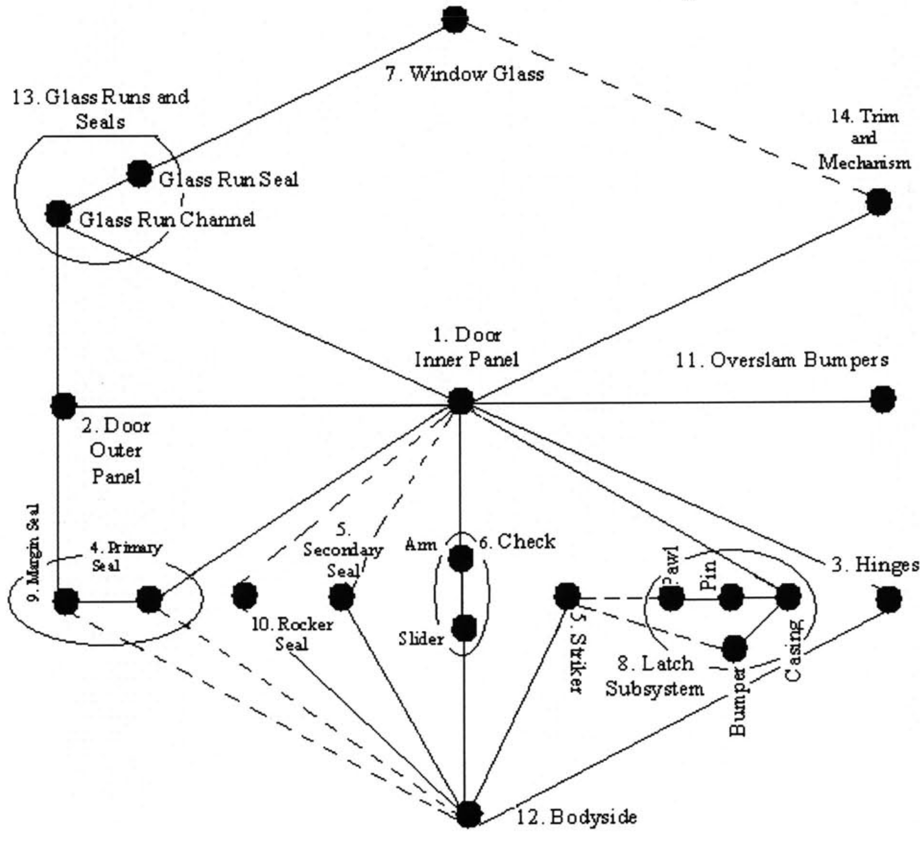


Figure 7.3: Liaison Diagram of Door Assembly

As stated before, the DFC would be a subset of the liaison diagram in figure 7.3. Essentially, all attributes flow through the door outer to door inner, to latch-striker interface and finally to the body side. Variations stack up and tolerance analysis ought to be arranged based on tracing these attribute delivery chains through the physical assembly chains shown above. This is largely the case when it comes to simulations for dimensional variation analysis at NA OEM. Below is NA OEM's attribute-related DFC:

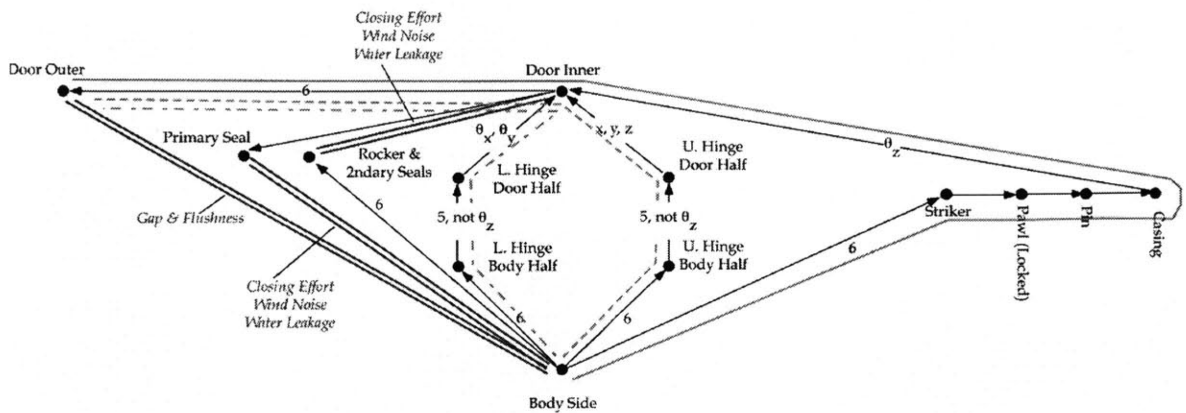


Figure 7.4: Datum Flow Chain for Door Case Study

In figure 7.4, the red double lines are showing key characteristics (same as customer attributes) and the green lines (dotted and solid) are showing chains of attribute delivery through the dimensional relationships between components. For instance, the seal gap and flushness attributes are delivered from the relationships between adjacently assembled parts (degrees of constraint labeled above): door outer to door inner to latch striker interface to body side.

A consistent method to convey assembly-related information such as the DFC is not used at NA OEM. Resulting amount of time spent on earning trust in data from cross-functional teams can be improved by adopting the DFC as a company wide tool. In addition the DFC also shows the various interfaces that need to be managed. Figure 7.5 is an example:

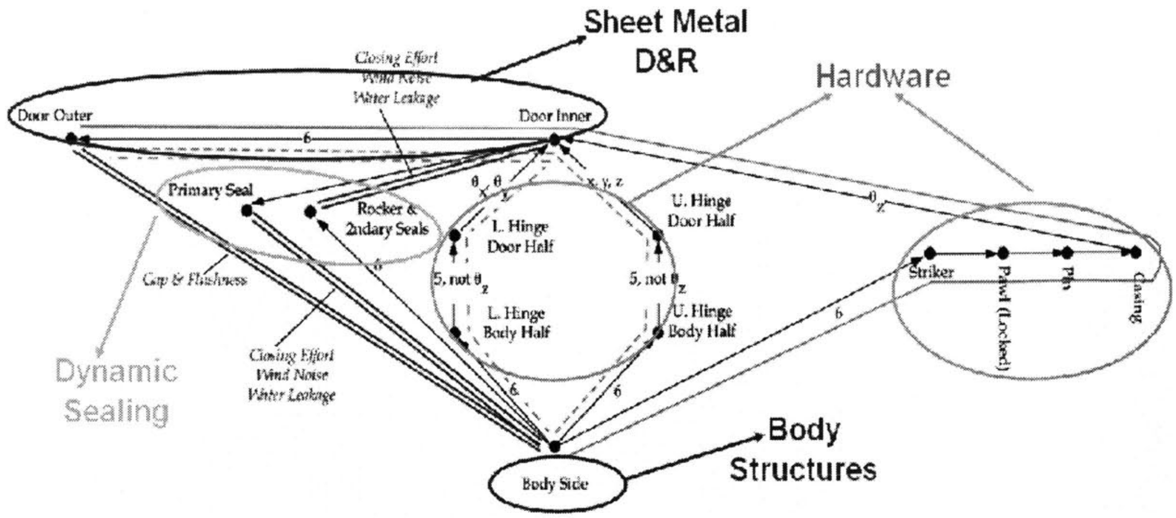


Figure 7.5: Organizational interfaces in DFC component design ownership

It can be seen that multiple groups affect the same attribute, which adds to the coordination challenge and requires a system integration role among engineers. In addition, the dimensional relationships are also delivered by various clusters:

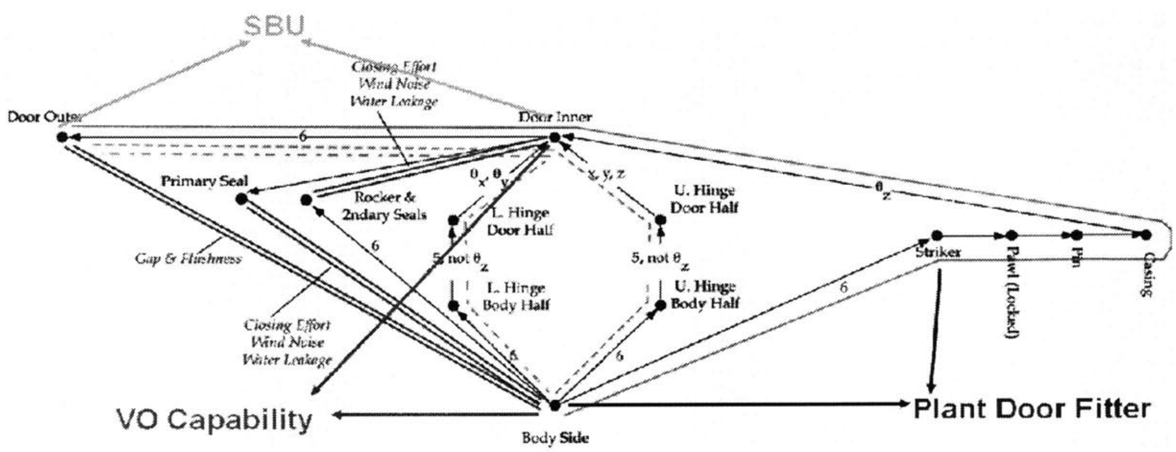


Figure 7.6: Organizational interfaces in DFC component assembly ownership

Figure 7.6 shows the Stamping, Manufacturing and Plant clusters are responsible to deliver the dimensional relationships needed for a quality product. Thus, the design team needs to coordinate with various manufacturing and assembly-related clusters. This again calls for an approach like simultaneous engineering at Toyota or the closures system integrator role at the NA OEM.

Variations

Seal gap variation is defined as follows (with differences from nominal or variation defined as ε): $\varepsilon_{SG} = \varepsilon_q - \varepsilon_i - \varepsilon_F$ and $\varepsilon_F = ((\varepsilon_S - \varepsilon_L) - \varepsilon_d) + (\varepsilon_f - \varepsilon_{Bp})$ where, ε_{SG} = variation in seal gap, ε_F = variation in flushness of assembled door to B-pillar, ε_q = variation in B-pillar flange location, ε_{Bp}= variation in B-pillar outer surface, ε_i = variation in location of door inner panel, ε_f = variation in flushness of door's outer surface, ε_d = variation in door apply fixture location, ε_S = variation in striker location, ε_L = variation in latch location, The following equation can be used: Flushness = (Striker – Latch) – Door location + (Door flushness – location of B-pillar) Variation formula uses a sum of squared errors. [Leeland, 1997]

Causal Loops

If the door is received in an outboard condition, it either must be bent inboard or B-pillar must be brought outboard to meet flushness specifications. Mismatch in latch-striker location has a similar effect. In both cases, seal gap becomes smaller and door closing effort also increases. There are inner loops that reinforce the causal loops. For instance, if the B-pillar is received under-flush, then the door header will be over-flush to the quarter panel. This causes the door fitters to bend the door inboard to match the quarter panel. This in turn causes the seal gap dimensions to become smaller, which increases the compressive forces. As the compressive forces on the door increase, the door is pushed outboard. As the door is pushed outward, it becomes over-flush to the quarter panel. Since this loop is reinforcing (not compensating), it says that having an input of a B-pillar that is inboard throws the system into instability.

Axiomatic Design Theory and Closures Design

Having gained several insights from the Design Structure Matrix and Datum Flow Chain, we make a brief comparison to lessons that could be drawn from Axiomatic Design Theory Axiomatic design is a methodology of connecting the conceptual domain (functional requirements or FRs) of a design to the physical domain (design parameters or DPs) [Suh, 2001]. This connection is made through a Design Matrix (DM) that connects the FRs and DPs.

The DM (not shown here for reasons of length) of door design is a complex one and from interactions contained in it, the design is coupled based on the existence of several above diagonal entries. When one DP (such as seal force) affects more than to functional requirements (for noise and effort), several system level tradeoffs have to be made. The structure of the DM for the as is process renders the following order of decisions on FRs:

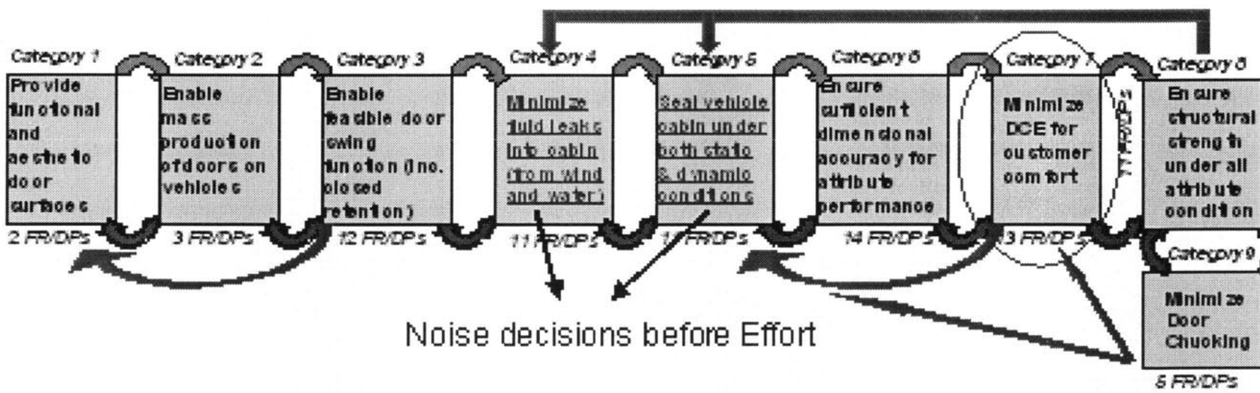


Figure 7.7: Decision structure and sequence of FRs and DPs based on Design Matrix

The above categorical order (timeline) of DP decisions in figure 7.7 shows that apart from a lot of feedback and coupling, the process is structured to finish the noise-related decisions first. Door closing effort seems more of an end result. It is interesting to note that the computer-based analytical tools for wind noise are lesser of a bottleneck and more accurate than effort related tools, which might explain some of the sequencing above. Because of their relatively greater accuracy, noise tools are used more frequently and even as early as the concept stage of the vehicle program. This points out to improvements needed in closing effort tools.

To summarize this chapter, a consistent method such as the Datum Flow Chain could improve the execution, coordination and communication of assembly related tasks at NA OEM. These tasks include variation stack up, assembly feature or structural constraint studies. In addition, the DFC is valuable in understanding the component interfacing and devising cross-boundary teams for component assembly. Axiomatic Design reveals the coupling of design parameters and execution sequence of functional requirements, showing that the wind noise is favored by the process at NA OEM. The next chapter has managerial considerations for process improvements.

8. Managerial Considerations

This chapter discusses some important implications for upper management from the results obtained thus far. The chapter also begins to make some suggestion that could help management understand the role of minimizing system interventions that derail the process and maximizing the role of system integrators. Research and insights from system dynamics are mentioned to support some of the content.

Overview of good practices in management

According to research by Ittner and Larcker, critical elements for process management success include:

Process focus: Management literature suggests that firms must bring individual activities or operations under statistical control before broader initiatives can be successfully undertaken. Subsequent measures of improvement can include value stream analyses or implementation of new organizational structures. *Human Resource Management Practices:* Whether the highest talent is attracted and retained is of critical importance. In addition, linking people's ability with the right type of tasks and keeping experienced or competent personnel in clusters that maximize their core competencies is very beneficial. For instance the average tenure of an engineer at Toyota is at least 4 years with the same team, while at NA OEM usually far less than 2 years. Training in problem-solving and coordination also helps.

Informational Utilization: A key role of management is to identify and eliminate causes of process waste using data. Examples of helpful tools for this are: SPC, Pareto, benchmarking, and design guides.

Customer/Supplier Relations: being able to coordinate product details beyond the four-walls of a company is crucial. Suppliers can provide the company with ideas, data and market intelligence needed for robust improvements. The relationship of Toyota with suppliers such as Nippon Denso is a clear example of this. Customer involvement in determining and testing system targets is very helpful.

Organizational Commitment: This is the degree to which an organization commits to improvement and teamwork. Process management efforts are unlikely to succeed otherwise. [Ittner and Larcker, 1997]

Creating incentives and metrics for the firm

A firm can only reward a very few, specific types of work practices in order to send a coherent message on performance expectations to its employees. For NA OEM, and many such large corporations, observations show a dichotomy between rewarding successful firefighting or contributing with incremental improvements – two mutually exclusive modes of operation. As discussed, NA OEM rewards engineers who are successful firefighters when the PD process is strained in terms of meeting timing, cost or quality requirements. However, such organizational culture leads to a colossal amount of waste in resources and lower returns on investment. On the other hand, firms such as Toyota reward engineering discipline and contributions to the advancement of organizational learning. It could be argued that a firm, such as NA OEM, needs to be out of the firefighting mode and utilize resources at stable levels to induce a culture of improvement-based incentive. The only was this could happen is if management prioritizes such a shift in cultural paradigms, invests the right amount of resources in improvement ideas and then follows suite by strictly avoiding any deviations.

Drivers for program changes in PD teams

Through this case study, it has been observed that management's knee-jerk reaction to industry reports and management hypotheses without sufficient data for back up are two drivers of change in direction for programs. These two reasons might arise from the lack of confidence in a struggling firm. Investment of constrained resources in tool development is not an issue at NA OEM, even when it comes to technical specialists. Resources assigned to current programs are given special studies, which take away from upfront development time needed in their own programs. This makes later fire fighting virtually guaranteed. In terms of cancelling projects with insufficient analyses upfront, Toyota is a prime example whereby it simultaneously develops multiple "solutions" to a given market need and discards all but one that is most feasible and has passed early stage conceptual tests. Management intervention at companies such as NA OEM is not only a driver of firefighting, but also affects viability the company.

Gear model applied to management decisions

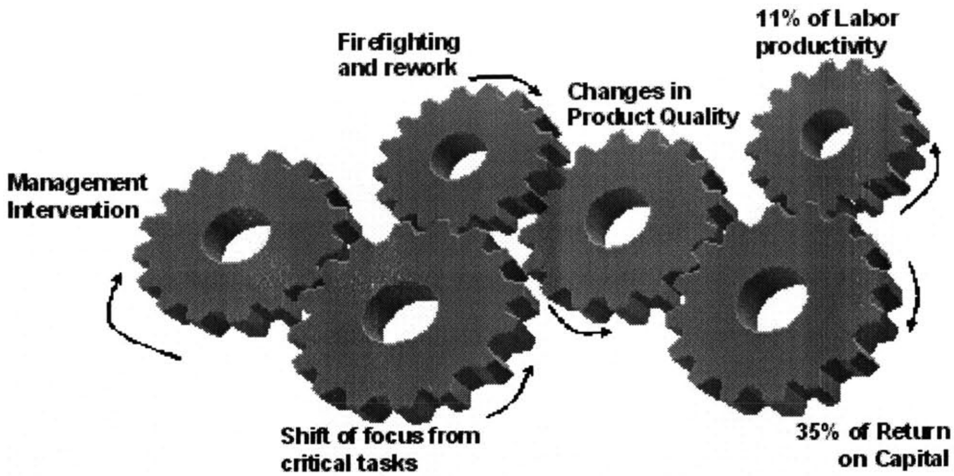


Figure 8.1: Gear Model for Management Practice

The above diagram in figure 8.1 has been developed combining statistics from the London School of Economics about the effect of management practice on returns on labor and capital, along with the Gear Model by Professor Charles Fine at MIT. When management assigns special projects or induces a change of direction in a high resource utilization firm, it leads to a shift of focus from critical tasks. As will be discussed in the tipping point section, a significant amount of firefighting and rework occurs. Resulting changes in product quality and customer satisfaction leads to low returns on labor and capital.

Effects of changes to programs

It is clear that unplanned changes imposed on programs compromise system performance. Moreover, such changes could sometimes be inevitable in a back-loaded process where early analysis is deficient. A host of research by the System Dynamics Group at MIT also covers the issues mentioned above.

System dynamics approach to program changes with DSM

According to Sterman and Ford, performance on projects is affected by the goals, resource availability, scope and development process (for aspects), all of which affect performance. Aspects such as scope can be revised based on externalities such as market needs or internal factors such as progress or performance. The four subsystems that interact in a product development process include (in the DSM), targets (milestones), scope and resources. Process metrics include time, defects and cost (figure 8.2).

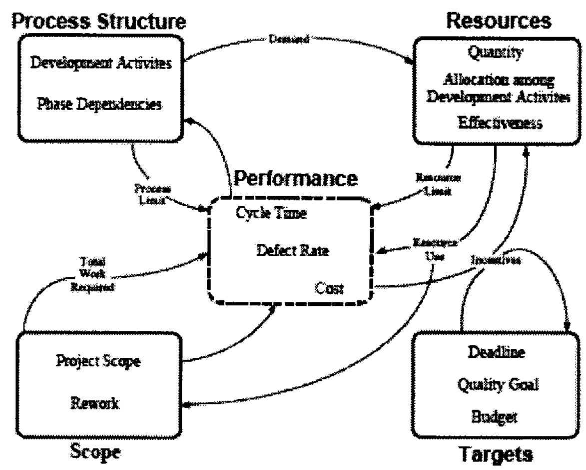


Figure 8.2: Phase subsystems [Source: Sterman and Ford, 1997]

Steps such as product definition, design, and prototype testing and reliability/quality assurance play a role in linking four aspects. The link between phases is in a project network (figure 8.3).

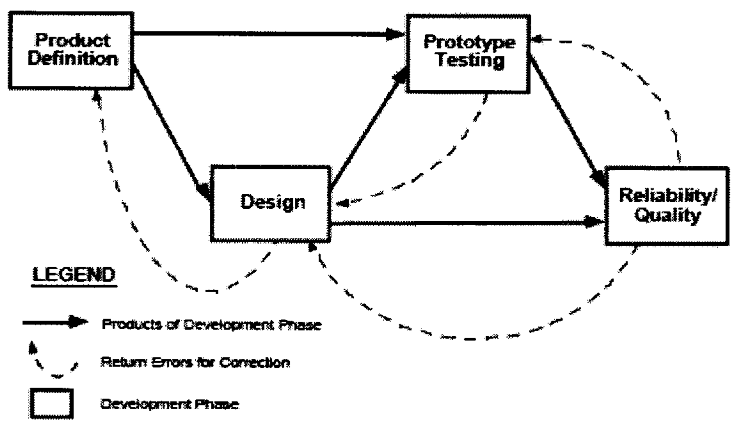


Figure 8.3: A Project Network Diagram [Source: Sterman and Ford, 1997]

Most development processes, in turn, are characterized by the difficulty of milestones, number of iterations and late changes. This is captured by "return errors for correction" in figure 3 above. The DSM is a useful tool for study work iterations. It is also important to incorporate quality assurance and coordination steps. The DSM represents the above phenomena in figure 3 in the following ways:

- Upstream WIP constrains downstream tasks

- Defects created in upstream processes are fed to downstream tasks, and when discovered, cause feedback of information to already completed upstream tasks
- Coordination required between phase that detects and phase that generates error
- Schedule, quality and cost at each individual task affects the performance of overall project, as defined by response of managers at each phase.

The four aspects affect each of the following sub-tasks for each PD activity:

- Initial completion: finishing the task for the first time during a project
- Quality assurance: inspecting the completed task for errors and improvements
- Iteration: carrying out more work on the tasks to correct errors or improve it
- Coordination: linking each task to related ones for project, especially downstream

Errors in a particular task that lead to rework in the PD process are caused by one or both of:

- mistakes internal to task execution and engineering
- mistakes handed to the tasks from an upstream, related task

The DSM helps capture the impact of both. The relationship between changes in task duration and overall project duration are not one-to-one; however, changes in initial completion time of tasks affect project durations most. The DSM simulation is able to capture this effect. Need for understanding aforementioned details goes up with project complexity. Also, current management techniques do not capture the complex interactions among project modules. In particular, feedback and iterative structures have not been accounted. While managers intervene with programs, they still expect consistent results.

System dynamics view of managerial intervention

In a system beyond tipping point of firefighting, such as the as-is PD process for closures where the average resource utilization is already about 81%, managerial intervention could be disastrous. System dynamics models prove that once a complex or highly coupled system reaches 80% resource utilization, small (unplanned) disturbances from a high number of task failures or externalities can trap the process in a firefighting more. Management's interventions become critical due to the dynamic in figure 8.4:

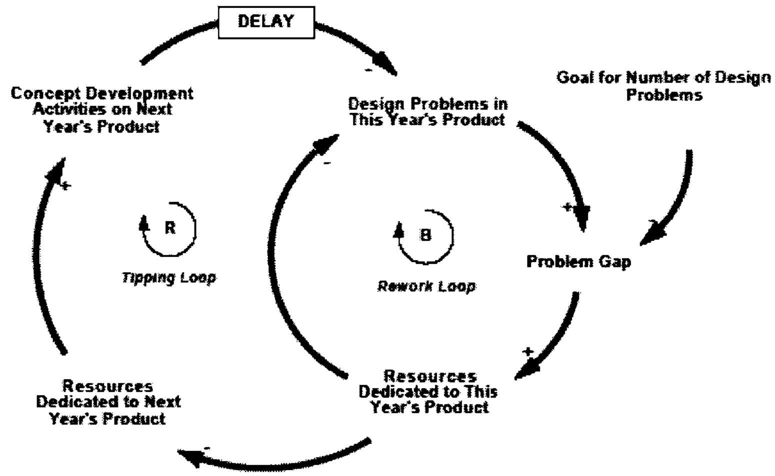


Figure 8.4: Reality of a system beyond the tipping point [Source: Repenning, 2003]

The above diagram shows why a small request or special project handed from management to engineers in NA OEM would destabilize the whole PD system. According to Repenning, Gonclave and Black:

- Fire fighting is related to workload and can permanently deteriorate performance of a PD process.
- The location of the tipping point in the process depends on resource utilization is steady state. When the resources are overworked, only small shocks are needed to cause serious firefighting.
- The tipping point affects the level if below which the amount of upfront analysis and conceptual work falls, the system can never break out of firefighting and rework.
- Assigning resources to special tasks moves the tipping point to earlier in the process. Managers do not understand dynamics of fire fighting so it persists. There are short term benefits of reassigning to special tasks, but long-term drawbacks. Because managers focus on the short-term, this is a reinforcing culture as short-term benefits are perceived to outweigh long-term negativity.

Apart from management practice, the organizational leverage given to system engineers or integrators sends a message on how important it is for the firm to deliver customer attributes at a satisfactory level. Therefore, it is important to create opportunities and reward good performance on system engineering.

Creating a better-aligned organizational structure

Due to component interfaces, simultaneous engineers or system integrators become essential in controlling the amount of rework and firefighting in an organization. Exchange of component information takes place across functional groups as shown by NA OEM's component interfaces:

Func. Group	Tasks Organized by Functional Groups	Tasks Sequenced for Info Flow in DSM	Loops
Sheet metal/interface	Door system stiffness (hinge pillar, striker surface and door sheet metal)	Number of seal walls (A-pillar and around door)	1
	Air extractor position (packaging for internal and external air access)	Mass and centre of gravity (sheet metal, trim, packaging)	
	Margin and Flushness DVA (includes striker, hinge and check position variations)	Door system stiffness (hinge pillar, striker surface and door sheet metal)	2
	Cheat in header and pillar (CAE based deflection from material, thickness, shape)	Hinge characteristics (stiffness, friction and torsional energy)	
Sealing	Number of seal walls (A-pillar and around door)	Margin and Flushness DVA (includes striker, hinge and check position variations)	
	Primary seal force (CLD and bulb dimensions)	Primary seal force (CLD and bulb dimensions)	
	Secondary seal force (CLD and bulb dimensions)	Secondary seal force (CLD and bulb dimensions)	
	CAE validation of seal interference	Cheat in header and pillar (CAE based deflection from material, thickness, shape)	
	Venting through weatherstrips (air trapped within/between primary and secondary)	CAE validation of seal interference	
Trim/Window Mech.	Mass and centre of gravity (sheet metal, trim, packaging)	Venting through weatherstrips (air trapped within/between primary and secondary)	
	Centre of gravity relative to hinge centre line	Latch type & characteristics (spring, height, size, energy, over travel, pawl vault)	
Closing h/w	Hinge characteristics (stiffness, friction and torsional energy)	Door cavity (latch, child lock) sealing between weatherstrips	3
	Latch type & characteristics (spring, height, size, energy, over travel, pawl vault)	Latch-striker interface (sliding vs. non-sliding or no wedge)	
	Latch angle relative to hinge centre line in design (particularly rear door)	Vehicle air leakage (uncontrolled amount)	4
	Latch-striker interface (sliding vs. non-sliding or no wedge)	Air extractor design (allowance, size for controlled leakage)	5
Protection Mech. (bumpers)	Latch bumper durometer (for chucking protection)	Air extractor position (packaging for internal and external air access)	
	Latch bumper interference (latch-striker load deflection curve)	Latch angle relative to hinge centre line in design (particularly rear door)	
	Over-slam bumper properties (stiffness, size)	Latch bumper durometer (for chucking protection)	
	Over-slam bumper interference	Latch bumper interference (latch-striker load deflection curve)	
	Bumper (for latch and overslam) durometer loss from ageing	Over-slam bumper properties (stiffness, size)	
Air Pressure	Air extractor design (allowance, size for controlled leakage)	Over-slam bumper interference	
	Door cavity (latch, child lock) sealing between weatherstrips	Bumper (for latch and overslam) durometer loss from ageing	
	Vehicle air leakage (uncontrolled amount)	Centre of gravity relative to hinge centre line	

Figure 8.5: Sample of component interfaces

It is an integrator's job to enable the mixing of the "colors" – functional groups shown in figure 8.5. In addition, handoffs and process-based interfaces also lead to the need of an integrator who coordinates and manages the handoffs in the PD process at NA OEM, as follows (18 handoffs with the Manufacturing organization, PD-Plant handoffs are inherently weak or incomplete, 58 handoffs in total):

(Part of Interface Diagram for Closures Design) GPDS	Weeks	10	21	40	46	51	55	59	63	72	80	86	94	108	130	138	140	147	162
Key: (X = direct interaction, x = indirect interaction)	Milestone	KickOff/FC0	PS/FC1	FC2	FC3/PSC	PTCC	FC4	PTC	FC5	AA1/SM	PA/AA2	M1DC	FDJ	VP	PEC	EC	LR	LS	J1
Manufacturing																			
MBO		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
VOGO																			
Pre-Prog																			
Final		x	X	X	X	X	X	X	X										
Body		x	X	X	X	X	X	X	X										
NMPDC																			
Program Management													X	X	X	X	X	X	X
Final													X	X	X	X	X	X	X
Final Operators														X					
Paint														X					
Body													X	X	X	X	X	X	X
Body Operators														X					
Production																			
Final														X	X	X	X	X	X
Paint														X	X	X	X	X	X
Body														X	X	X	X	X	X
Dimensional Control																			
DVA				X	X	X	X	X	X	X	X	X	X						
Tooling/Locator Development									X	X	X	X	X	X	X	X	X		
SBU																			
Pre-Program				X	X	X	X	X	X	X	X	X	X	X					
Production									x	x	x	x	x	X	X	X	X	X	X
Production Assembly Plant																			
Area Managers / Supervisors / Engineers																X	X	X	X
Operators														X	X	X	X	X	X
PD - Functional Management (CFE led)																			
PVT																	X	X	X

Interfacing Teams	Sub-teams (# of interfaces)	Minimum # of handoffs
Marketing	1	0
Studio	4	4
Resource Planning	1	0
PD Digital Creation	1	0
Material Planning and Logistics	3	3
Program Management	2	2
Program Finance	2	2
Body Integration	2	2
Functional Management	15	15
Manufacturing	18	18
Body CAD	4	4
Purchasing	1	0
CAE	3	3
Testing Facilities	5	5
Total	**62**	**58**

Figure 8.6: Snapshot of process interfaces and overall summary of handoffs

Owing to details in figure 8.6, NA OEM has created system-level positions in the closures team. While results are promising, several improvements are still needed. We begin with a brief description of these positions in this chapter and discuss details in later ones.

An introduction to systems engineering positions

The position of Closures System Integrator (or CSI) in PD was created to enable a system focus and better performance on attribute balancing. The aim of this position and project was delivering more robust door systems that meet customer requirements on attribute conflicts. Design and release of components and CAD drawings would not be a major responsibility of the CSI (as opposed to the Supervisor of Design and Release). Some of the observed benefits of the CSI position include:

– Improved communication within PD and interfacing teams

- Balances attributes (e.g. wind noise and effort) early in design stage
- Links reporting chains for effort (in Closures) with Others (external)

The CSI does not have signoff authority on designs and serves in an advisory role, which sometimes leads to lesser organizational leverage than required to implement system decisions.

CSE in PD (and proposed for plant and other teams)

The PD team also has a designated engineering working under the CSI to support system tasks. This is called the Closures System Engineer or CSE and is much like a deputy CSI role. However, such a position is missing at NA OEM plants, where a concerted linkage of different attributes with problems like warranty issues are also important. Also, a CSE-type person at the plant would facilitate better knowledge transfer between the PD team and the plant team, which is ultimately responsible to fix warranty complaints on a product they rarely had the chance to interact with before launch or during PD.

Examples: pertaining to doors and others

As inferred from Toyota, the following characterize a desirable PD process [Morgan, 2004]:

- Toyota process is very front loaded. NA OEM should strive for this
- Adherence to defined timeline and milestones of PD process
- Manufacturing is should be well-represented (not well-represented in NA OEM's early PD)
- Benchmarking should be a priority. Benchmarking is inherently different at the two OEMs – e.g. teardown results shared with all PD participants at Toyota

As the CSI and CSE have a role in system engineering and coordination at NA OEM, at Toyota, simultaneous engineering responsibilities lie with the whole Production Engineering group (figure 8.7):

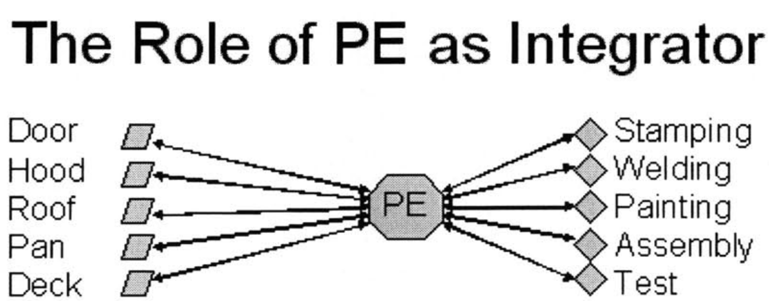


Figure 8.7: Production Engineering at Toyota [Source: Whitney, 2007]

According to Whitney, PE works with its own special skill areas to understand how to respond to designs and forges a consensus response and suggestion. PE also works with car design areas to understand the design and make the suggestions. Whitney also presents a comparison of Toyota and NA OEM from an organizational perspective as shown in figure 8.8 below:

System Comparisons

- NA OEM (CSI)
  - The system has a single point of contact and responsible person
  - That person is in PD
  - The credibility of manufacturing in PD is not strong
  - The involvement of manufacturing is not strong, persistent, or consistent
- **Toyota (generally)**
  - The system has many eyes on it
  - Many of those eyes are in PE
  - The involvement of PE is strong to the point of dominance
  - This involvement begins during styling

Figure 8.8: Comparison of Toyota and NA OEM [Source: Whitney, 2007]

Again, while NA OEM is headed in the right direction with the CSI and CSE, a lot more support from management and further improvements are desired. In this chapter, we see managerial considerations and implications of lessons from an industry leader. In the next two chapters we present some further organizational analyses at NA OEM and ideas on how to manage change for improvement in a challenging market environment while maintaining product deadlines at the same time.

9. Further Organizational Analyses

This chapter discusses some NA OEM-specific organizational observations. A significant set of conclusions and recommendations are drawn from an extensive organizational survey that was carried out at NA OEM to collect data on the integrator roles in PD.

Structure of Teams for Components and Attributes

In the PD cluster, teams are divided into three broad categories that merge only at the highest level of company management: Functional, Attributes-based or Program management oriented. A brief discussion of these teams (as a reminder to the reader) follows next. The design-related teams are organized by signoff authority on attribute performance or component design delivery. These are called attribute-based or functional teams above. As discussed in earlier chapters, there is a designated team to deliver the wind noise attribute in general. The team cascaded targets down to the door system and monitors performance. On the other hand, there is a team with the responsibility to design components and the sheet metal for doors, which also has the ownership of the closing effort attribute. The fact that reporting chains are different for coupled customer attributes on the same system is peculiar to NA OEM.

In general, most teams are based on this design and release responsibility and ownership of attributes is at times unclear, and occasionally conflicting. For instance, the NVH (noise, vibration and harshness attribute of which wind noise is a subset) team seeks to seal the vehicle cabin as tightly as possible to reduce external noise for entering the vehicle. However, the sheet metal design and release would like the air leakage through the cabin as large as possible in order to help release the pressure wave during the action of closing the door, which would then reduce the amount of effort required of customers. Program management oriented teams track attributes such as cost and weight and also monitor the delivery of completed tasks with respect to the program schedule. Such reporting chains fall under the chief nameplate engineer, who supervises a launch manager (to facilitate the smooth start of production).

DSM vs. PD Process sequences and team structures

If there is one insight from the DSM about team structure, it is that process integration through simultaneous engineering and/or system integration (starting with the CSI role) is a significant need for successful execution of the process. Initiatives such as the CSI role have to transcend sub-system or system boundaries and need to be presence in all parts of the vehicle program's system.

The role ought to include integration with non-PD clusters and across different attribute reporting chains of various natures (functional versus designated). This insight is supported by independent research.

Haddad performs an extensive study on the impact of team structure and level of coordination on a company's performance. One company was successful in shortening concept-to-market time by over one year on its first newly designed vehicle, primarily through the use of product-focused, cross-functional platform teams which permitted the early integration of manufacturing personnel into product and process development. Organizational and human resource changes were the greatest enablers. [Haddad, 1996] We now move onto more specific results from organizational surveys and data collected to analyze the success and improvements for system-level roles at NA OEM.

Impact of System Engineering at American OEM

The Closures System Integrator and Engineer (CSI and CSE) roles at NA OEM have been a clear success in terms of their benefit to product quality.

PD closures system integrators and engineers

It has been proven for the first time at NA OEM that a system-oriented engineering role is both needed and successful. It is hoped that not only will the CSI role be strengthened, but that it would also be disseminated to other parts of the vehicle program such as seating or body design

– areas that could also use attribute balancing and system-level decision making from the start of the new programs.

The following shows the progression of system-related design issues discovered at the same stage of three vehicle programs with various level of CSI/CSE involvement:

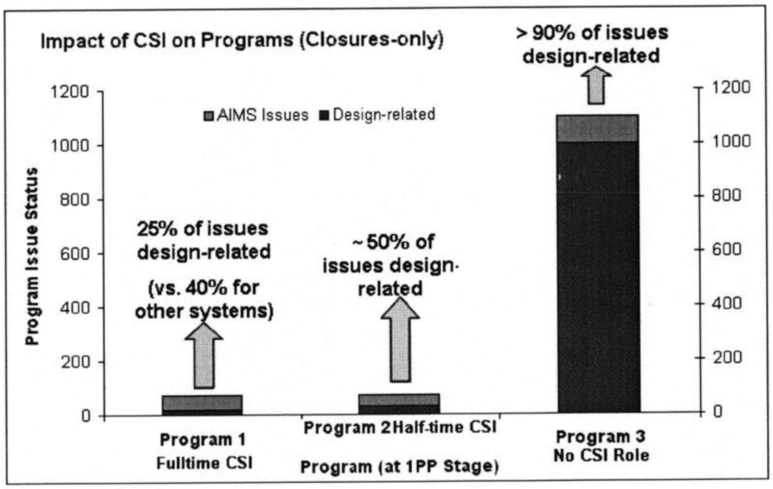


Figure 9.1: Impact of Closures System Integrators on Programs

As shown by figure 9.1, with no closures system integrator, the number of door issues at launch for program 3 was the thousands. 90% of these related to design decisions. Though program 3 is known to have new door architecture that would inherently increase unresolved design issues, the stakeholders involved agreed that a significant amount of these issues arose due to lack of system integration. Program 2, with a CSI present through half its length is much better with less than 100 total issues related to closures, only 50% of which are traceable back to design stage decisions. The best performance occurs on Program 1, when there is a fulltime CSI: only a quarter of the total issues encountered in closures are design stage decisions, whereas this number is close to 40% for the program

Manufacturing closures system integrators

The PD CSIs and CSEs have a total of 3 counterparts in the manufacturing organization, and these are called the Manufacturing Closures System Integrators (of Mfg. CSIs).

Mfg. CSIs are not assigned to programs on a fulltime basis but serve, at best, in a support role. They have spent 80% of their time on standards and documentation, which is a sharp contrast to the PD CSIs who spend most of their time on day to day design tasks, which is far from their ideal role. This is useful to improve manufacturing knowledge, however; the program support given by Mfg. CSIs is deemed insufficient. Interviews with CSIs from both the PD and Manufacturing organizations confirm that more support would reduce the amount of rework that arises from insufficient integration of assembly and design decisions. This might be accomplished by raising the head count of Mfg. CSIs from three to at least the number of PD CSIs that ranges between six to eight (when the above observations were made).

Study on system engineering roles at OEM

A survey was conducted to gather more formal feedback on the performance and opinions from the CSI position. Data used in this report are based on these sources:

1. Virtual attendance at Closures System Integrators Tech Club meetings,
2. A survey of CSIs/SEs along with some questions for Mfg/Tech Specialists
3. Interviews and other communication with various stakeholders

The CSI Tech Club meetings occur once a week (or less depending on discussion topics) and have been instrumental in identifying the right contacts for interviews, understanding day-to-day issues faced and solved by CSIs, and both circulating and collecting the survey this year in a voluntary, confidential and anonymous manner. The response rate for the CSI/SE survey was a healthy 83.3% (20 data points).It is important to mention that a similar endeavor was carried in April, 2004 to gather feedback from the various parties involved in closures systems. The result was a similar report from data using the same sources. The new survey was designed using the old one as basis, and some questions were repeated from the old survey (that had a response rate 67% for seven data points per question) to compare for progress and assessment changes.

i. Areas of Study

Owing to the design of the survey and scope of the CSI/SE roles, the outcomes of our observations are arranged in the following categories:

1. Impact on System and Process (about one-third of total questions in survey)
2. Job Performance and Satisfaction (about one-third of total questions in survey)
3. Support & Resources (about one-third of total questions in survey)

There was space allocated for comments and suggestions on the survey questions as well. Similarly, comments obtained through interviews and points of discussion in the CSI Tech Club meetings also fall under the same categories. Some questions were designed to capture the impressions of Manufacturing, Resident Engineers at Plant (REPs) and Technical Specialists on the CSI/SE role in the PD cluster. Response rate was 100% and sample size was 10. Note that on the new 2006 survey, the scale definition to answer quantitative questions is: *1 means strongly disagree; 7 means strongly agree*

ii. Positives

The CSI position has significant positive impact on several closures-related aspects.

1. Impact on System and Process

On average, the respondents spend 55.5% of their time at work on system level or door attribute issues. While this number falls in the "higher the better" category, spending about half the time on system issues is a good start. On the (1 – 7) agreement scale defined, the CSIs/SEs are at a 5.1 regarding their impact on improved attribute performance of the door system. Notice this is the second highest agreement level for any question on the whole survey. The integrators and engineers agree at a medium-level (average of 3.8) that they have actually created tools for system analysis and diagnosis. Again, this is a good start that can be further formalized and improved upon. There is relatively good agreement on the role helping reduction in rework (an average score of 4.6). There is strong consensus (among 16 of 19 respondents) that the CSI/SE role has helped improved communication within the PD team, and good consensus (among 12 of 19 respondents) that the position has helped improve communication between Manufacturing and PD teams. The CSI and SE roles have certainly had positive impacts on the door system and product development process.

2. Job Performance and Satisfaction

As per the impact of the role on personal and intellectual development of CSIs and SEs, there was good agreement (4.9 on average, and 7 for the mode) on the positive impact of the role in developing good engineers at NA OEM. Similarly, most CSIs/SEs agreed that they would take the position again (average of 4.3 on agreement scale although a couple of engineers would strongly disagree and selected a score of 1). Most (at least two-thirds) CSIs/SEs agreed that their roles and responsibilities (R&R) are clear with the following: D&R Supervisor, PMT Lead, System Engineer, Body CAD EDA. However it is to be noted that these interacting entities lie within the same PD clusters, which could explain high R&R clarity. CSIs and SEs seem to be most satisfied with the amount of engineering work on programs and other minor, miscellaneous things they have to do (average discrepancies on current and "should be" time spent smallest at -3% for these activities).

3. Support & Resources

In general CSIs/SEs feel (with an average agreement score of 4.7) their management is mostly supportive, helpful and receptive of their roles. This, along with the opportunity to develop skills, explains some of the reason that most of these engineers and integrators would be willing to take the same position again on a new program. In general (with an average score of 4.2), the CSIs and SEs also feel the have sufficient training for their jobs. However there is room for improvement in training – this training possibly comes indirectly through job experience, as there are not many formal courses of instruction. Basically, a new CSI or SE with little or no prior experience in closures would have a tough time going up the learning curve. Standardization through developing standards and process details would be helpful in overcoming this difficulty.

iii. Areas for Further Improvement

As gathered from the recent focus on R&R at the Tech Club meetings and survey results areas of improvement are broken down to three categories:

1. Impact on System and Process

The CSIs and SEs feel they do not have sufficient opportunity (such as from time available on the job) to develop system analysis and diagnostic tools (an average score of just 3.5 on the agreement scale). This means that the actual tools they have created were extremely necessary and the opportunity to develop these tools had to be created with personal initiative. It also means that such tools are not institutionalized. In fact this is indicated by an average score of just 3.8 on the impact of CSIs/SEs for standardizing processes and a strong desire to spend more time on development of standards (Table 5, pp 6). Lastly, despite good agreement on betterment, PD engineers feel communication with manufacturing needs further improvement.

2. Job Performance and Satisfaction

The biggest area of improvement for CSI/SE positions is defining and formalizing R&Rs:

i) Agreement score on this need is 6.1 on average (highest for all questions). This need of clarifying CSI/SE tasks creates a "pull"[1] situation for change.

ii) Agreement score on whether R&Rs are currently defined to a satisfactory extent is a low average of 3.4 but not as low as the "pull" of (i) would suggest. It possible that CSIs/SEs implicitly define their own R&Rs as they go.

iii) Most of the CSIs/SEs strongly disagree that their career path is well-defined after taking the position at NA OEM (that is an average agreement score of 2.1 – lowest of all questions, and a high score of just 4). This combined with (i) and (ii) creates performance issues.

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[1] Klein, 2004, True Change, John Wiley and Sons: San Fransisco, CA

Not only the R&Rs, but the CSI/SE career path needs further clarity. Furthermore, there are also some specific task and role pointers. Most (about two-thirds) CSIs/SEs agreed that their roles and responsibilities (R&R) are not clear with the following: Block Leader, Electrical, PAT Leads, Studio and PPC. About half say the R&Rs are unclear with Body Engineering SIs, Manufacturing CSIs, and attribute teams (vehicle engineering). Note that these interacting entities mostly lie outside PD clusters, which could explain low R&R clarity and need for bridging gaps. CSIs/SEs seem to be most dissatisfied with amount of firefighting (wanting a 22% reduction from current average time spent), system coordination, system analysis and developing standards (want nearly a 10% increase in time spent on each of the last three activities on average. The CSI/SE management can be instrumental in preserving the roles, maximizing their benefit to the closure systems and giving them more direction.

iv. Support & Resources

Agreement level on sufficiency of personnel and resources to finish system tasks by deadlines is just a 3.4 on average. This is self-evident, but difficult to change. Even lower agreement (2.9 on average) is on the CSIs having the required organizational leverage to complete their tasks. However, this can be changed by slightly redefining the role's interfaces and bringing CSIs on decision footing that is similar to D&R supervisors. Lastly, the agreement on CSIs/SEs having time for development of system resources is on the lower end with an average of 3.7 on the scale. This ties into resource availability. In the next section, tables 9.1 – table 9.5 provide some of the key information gathered from the aforementioned, extensive organizational survey designed and administered specifically for NA OEM.

Details on aggregate results were analyzed. Results from the 2004 survey and report also provide insights on how the role has evolved over time. Following show the 2006 data results vis-à-vis 2004 results:

1. R&R

Survey Question # 17. Are R&Rs clear for following groups relative to closures system integration/engineering?				
Role	**Yes % (2006)**	**Yes % (2004)**	**No % (2006)**	**No % (2004)**
Block Leader	24%	NA	76%	NA
Body Engineering	42%	100%	58%	0%
Manufacturing Integrators	37%	60%	63%	40%
D&R Supervisors	63%	100%	37%	0%
Electrical	39%	50%	61%	50%
Management leads	61%	100%	39%	0%
Program leads	39%	40%	61%	60%
Studio	33%	0%	67%	100%
VE Attribute Teams	42%	67%	58%	33%
Manufacturing	47%	67%	53%	33%
Production Planning	29%	100%	71%	0%
System Engineer	67%	NA	33%	NA
Body CAD	72%	NA	28%	NA

Table 9.1: R&R Clarity Comparisons

For the same reference roles, R&Rs seem to have become less clear as time has passed because the CSI has more interface questions in mind.

2. Communication

Survey Question # 18. Has the SI/SE position improved communication?				
Interaction Cluster	**Yes % (2006)**	**Yes % (2004)**	**No % (2006)**	**No % (2004)**
within PD	84%	100%	16%	0%
between PD & Manufacturing	63%	71%	37%	29%

Table 9.2: Communication Improvement Comparisons

Opinions on the CSIs/SEs improving communication are the same - basically a yes. But there is still room for improving PD-Mfg. communication.

Communication quality and clarity of interactions with other contacts will increase with clearer definitions of R&Rs and deliverables.

Similarly, we can compare how the time spent on different roles has evolved over the last two years by overlaying data (next page).

3. Time Allocation

Survey Question # 19 first part. What percent of your time are you *currently* spending in each of the following areas?						
Task Description	**Low % (2006)**	**Low % (2004)**	**High % (2006)**	**High % (2004)**	**Mean % (2006)**	**Mean % (2004)**
Firefighting	0%	15%	80%	100%	30%	43%
engineering work on program	5%	0%	70%	30%	23%	24%
systems coordination	10%	0%	70%	30	23%	11%
systems analysis	0%	0%	30%	30	14%	14%
developing standards	0%	0%	15%	5	4%	2%
Other	0%	0%	50%	10	8%	2%

Table 9.3: Current Job Allocation Comparisons

CSIs/SEs spend lesser time on firefighting and more time on system coordination. System analysis and program engineering are unchanged.

Survey Question # 19 second part. What percent of your time are you *should be* spending in each of the following areas?						
Task Description	**Low % (2006)**	**Low % (2004)**	**High % (2006)**	**High % (2004)**	**Mean % (2006)**	**Mean % (2004)**
Firefighting	0%	5%	20%	10%	8%	9%
engineering work on program	5%	0%	60%	20%	20%	26%
systems coordination	10%	10%	70%	40%	30%	20%
systems analysis	5%	30%	40%	50%	22%	33%
developing standards	0%	5%	70%	20%	14%	9%
Other	0%	0%	60%	10%	5%	1%

Table 9.4: "Should be" Job Allocation Comparison

Currently, CSIs/SEs want more time spent on coordination as compared to analysis. This points to interface and communication challenges.

Analysis of Discrepancy in Two Parts of Survey Question # 19: Difference between current and should be numbers [sb - c] for % time spent per task						
Task Description	**Low [sb - c] (2006)**	**Low [sb - c] (2004)**	**High [sb - c] (2006)**	**High [sb - c] (2004)**	**Mean [sb - c] (2006)**	**Mean [sb - c] (2004)**
Firefighting	-75%	-95%	0%	-10%	-22%	-34%
engineering work on program	-50%	-10%	40%	20%	-3%	2%
systems coordination	-25%	0%	40%	40%	8%	9%
systems analysis	-10%	20%	30%	35%	9%	19%
developing standards	-5%	0%	70%	20%	9%	8%
Other	-45%	-11%	10%	0%	-3%	-2%

Table 9.5: Comparison of Difference between Ideal [sb] and Current [c] Time Spent on Job Tasks

Although not as much as 2004, the CSIs/SEs want a further reduction in time spent on firefighting, and a smaller increase in system analysis.

These results provide a good baseline for coming up with more updated and R&Rs to satisfy the "pull" for such changes.

v. External (Manufacturing SI/Plant/Tech) Stakeholders' Opinion

Most external stakeholders would like to see an increased level (content quality) and frequency of system design communication with their product development counterparts in closures (average agreement score of 3.5 for current communication). This shows the stakeholders are genuinely interested in helping out. Also, the agreement that the external stakeholders receive information details they need from PD to fully accomplish their tasks could also be improved from its current average score of 3.8. However, these external stakeholders generally feel (average agreement score of 4.7) that the PD CSI/SE position has made it easier to design more robust door systems. This is an encouraging sign for PD, which would certainly benefit from formal feedback of external stakeholders in closure systems.

vi. Conclusions

Based on data, observations and interviews we can make some relevant conclusions.

1. Effects of Amount of Time Spent in CSI/SE Roles

These can be studied using some correlations between [numeric answers to survey questions] and [number of months spent in the role]. We find that the more time a CSI/SE spends in the role, the more helpful in improving door attribute performance, the more the CSI/SE feels that the role has helped in personal development as an engineer, and a greater perception that the management is helpful, receptive and supportive of the CSI/SE role – possibly due to formation of close working relationships over time. There is intrinsic value for NA OEM to keep the CSI/SE on the same program for an extended timeframe. It is also seen that the amount of time spent on firefighting goes up with how long the CSI/SE has been in the role. This has to do with the fact that rework and changes occur after the initial stages of a program and more towards intermediary or late stages such as vehicle prototype (VP) build in NA OEM's PD PROCESS. However the more time spent in the role, the stronger the opinion that amount of firefighting should be reduced. Manufacturing-PD SI interaction for closures also becomes more well-defined with more time spent in role. Observations confirm the value of experience in the role.

2. Further Analyses

Another way to represent the breakdown of job time (as collected) is given below:

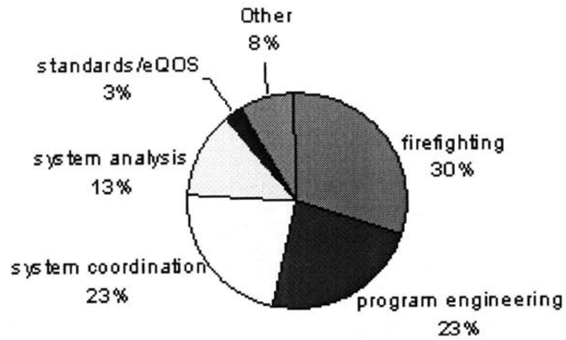

Figure 9.2: Current job time allocation

75% of PD CSIs spend less than 10% of work time on standards development. Some CSIs spend as much as 80% of work time on firefighting/design and release. Mfg. CSIs spend 80% of their time on developing standards/practices (ideal). This is how the CSIs would prioritize:

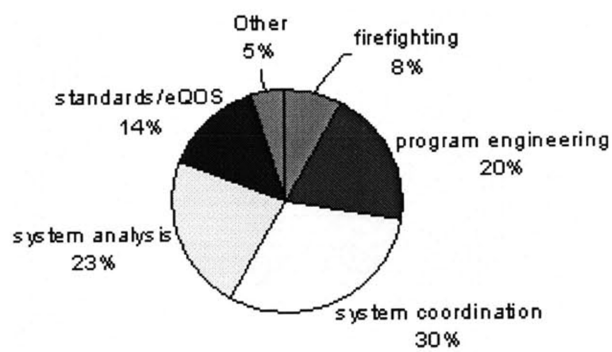

Figure 9.3: Desired job time allocation from interviews

Any revision to CSI/CSE roles and responsibilities should take the above into account.

3. Next Steps

The results of the current survey endeavor and this report were presented and discussed with all survey participants (in/outside of PD) as well as CSI/SE managers. Similarly Management's feedback on questions was also gathered and relayed to CSIs. The CSI/SE positions had a positive impact on communication, system design and robustness. The direction is right, and the momentum needs to be kept up with more support, training and clearer definitions of roles for CSIs on each program at NA OEM. It is up to management to prioritize this initiative. **However, just this month it was found out that the number of CSIs has been reduced to only two (one for car and one for truck programs).** The next chapter covers some further considerations for managers to induce an organizational change in NA OEM for performance improvements.

10. Managing Change

Changing the culture of any existing organization, large or small, new or old, is a monumental challenge that needs the application of best practices adopted to the reality of the firm. NA OEM's case as a large and well-established is an even bigger challenge.

Changing for a changing industry landscape

According to company figures (obtained from BBC), Toyota sold 2.348 million vehicles in the first three months of 2007. General Motors (GM) is estimated to have sold 2.26 million cars and small trucks during the same period. As of April, 2007 Toyota is the largest automaker in the world. But Toyota spokesman Paul Nolasco said overtaking GM was not Toyota's first priority. "Our goal has never been to sell the most cars in the world," Nolasco said. "We simply want to be the best in quality. After that, sales will take care of themselves." Simultaneously, talks for another sale of Chrysler are in the works. As of March, 2007 Ford laid off one-third of its salaried workers including as engineers. Korean companies such as Kia and Hyundai are at the forefront of quality improvements, while German automakers keep leading with novel designs [British Broadcasting Corporation, 2007] The landscape of the global and US automotive industry is constantly changing. Arguably this industry along with the airline companies forms one of the most constrained segments of corporations. Consequently, changing a firm's culture for improvements such as those needed for NA OEM is far from trivial.

Changing a firm's culture during hard times

There are three approaches to changing a firm's culture in hard times for an industry. Briefly, one approach is to bring lots of well-trained and experienced outsiders with the decision making power and necessary resources to induce changes to meet pre-defined goals within a set timeframe. This is usually tantamount to inducing a foreign enzyme to a living organism, whose immune system would most likely reject the change. On the other extreme, the firm could rely on the existing personnel and upper management to brainstorm ideas and quickly come up with ways to implement a cultural change in the firm. This, at best, is optimistic because the existing stakeholders would have become used to the same way of doing things. In other words, inducing change by depending on existing approaches and management styles is futile. The best of the two worlds succinctly described above would be a hybrid approach. The research done for this case study shows that inducing organizational change that brings fresh perspective while understanding and leveraging the existing culture gives the best chance of success. The insider-outsider approach would be most suitable. [Klein, 2004]

The Insider-Outsider Framework as an approach to change

This methodology for organizational change is more than a cookbook: it is a way of thinking and inducing true reformation from the grassroots level that successfully shapes the future performance. The framework entails using the strengths of the firm's existing culture (such as strong managers) to bring in new ideas that jump start improvements. Following are some elements of this framework for managers.

Managing and Leading the Self

Mr. Mandela famously said: "As we let our own light shine, we unconsciously give other people permission to do the same. As we are liberated from our own fear, our presence automatically liberates others."[2] As shown by Mr. Mandela's life example, overcoming one's fears is the only way to becoming an effective leader [Goleman, 1995]. Only as a strong, confident person could one ever lead others. A good leader is able to both create a crisis to induce a sense of urgency, and lead through a crisis. Ability to craft a pull for change and having strength of character in a crisis are invaluable qualities to cultivate.

Clarity of Vision and Formulation of Goals

One of the key elements in commanding respect from one's peers and followers is to have a clear vision and well-defined goals. Passion for one's goals and the drive to achieve them

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[2] Mandela, Inauguration Speech, 1994

serves as catalysts for success. Martin Luther King's historic *I have a Dream* speech in 1963's "March on Washington for Jobs and Freedom" [3b] is an embodiment of this clarity of vision, formulation of noble goals and a passion to make the impossible happen. The civil rights leader left no ambiguity that racial acceptance and equality are self-fulfilling visions upon which the goal of American democracy and freedom depends. Managers would not perform to their potential unless they were passionate about the objectives. The "why" is as important as the "what" and the "how" for a team's goals. Whether it is a small project, a corporate turnaround, or a human rights movement, a good leader has to show a clear vision and define lofty goals. Big success stories do not usually come from understating the goals and exceeding expectations (which might be helpful in a routine job). Big success stories come from defining the unimaginable and then carving a path to reach it. In addition, use of resources and talents is optimized when all sides agree on target results that become the strongest motivator. A leader is a pillar of unity and leads by example. The strength of managers is collaborative and distributed leadership instead of top-down leadership.

Flexibility to Adapt

Bono is arguably the world's most famous and greatest rock star. Over the last two decades, his band U2 has gradually risen to the epitome of stardom and it continues to be the largest generator of tour revenues among all artists. Bono has kept U2 united and its passion for music alive. Yet, he also has a separate agenda besides rock music. During his volunteer work in Ethiopia in the late 1980s, Bono found his other mission – eradicating world poverty. Besides his personal charisma, humility, and mastery of facts, it is solely Bono's flexibility to adapt to his audience that has enabled him to convince world leaders at the G-8 summit to cancel over $50 billion of African debt.[4] When he talked to Bill Gates for his support, Bono showed how much he knew about economic development issues, thanks to personal lessons from Professor Jeffrey Sachs. When he met with President G. W. Bush at the White House in 2002, Bono quoted scriptures and spoke of God's blessings on the work with poor, thanks to

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[3b] King Jr. and Washington (ed.), A Testament of Hope : The Essential Writings and Speeches of Martin Luther King, Jr., 1986
[4] Time, "Person of the Year", December 26 Ed., 2005

his upbringing with a Catholic father and Protestant mother. Adaptability is a key to leadership success.

Today's workforce and ideas are evolving in response to market realities as described for the automotive industry. This simply reinforces the value of being an outsider at the inside.

Questioning the Status Quo

To lead for the continuation of the status quo usually ends in mediocrity, but to lead for "true change" often ends in greatness. Managers always inherit a given way of thinking and of practice. However, their actual value as pragmatic thinkers and meaningful executioners would only be shown with improvement.

In the research conducted at NA OEM, one of the biggest facts found was the strong tendency to adhere with the status quo at the inside of the firm, and indifference to outside perspectives. Questioning the status quo and brining in change does not mean trying to discard the culture. In fact, it is the existing culture and practice that create the need or a "pull" for change. This pull can be based on various shortcomings, e.g. lack of benchmarking or self-improvement – all requiring an outsider's perspective.

Picking the Right Battles

Under the framework for organizational change that is presented in this chapter, this decision of where to focus is based on:

- How passionate are managers to work on a particular idea or project, and why?
- What type and amount of impact will it have for people involved and affected?
- Will it help their growth and understanding of something new about the firm?
- Will it lead to a *sustainable* improvement from the status quo at the firm?

For managers on new projects, the answer to at least three of the questions ought to be a yes.

Knowing When to Follow

A good leader knows that one does not always have the right answers. A great leader recognizes this and knows when to follow others. The importance of knowing when to be a good follower cannot be overstated. To get to the right place and remove doubts, Sir W. Churchill, as First Lord of the Admiralty, quietly followed Prime Minister Chamberlain's directions. Yet, Churchill did suggest preemptive strikes and set the stage for his future. Eventually it was proven that Chamberlain's war strategy was a failure. Churchill was appointed as Prime Minister, and became Minister of Defense. Despite his bold leadership, Churchill still chose to follow his aides – one example is putting his industrialist friend Lord Beaverbrook in charge of defense manufacturing.[5] Due to the production and business expertise of Beaverbrook, Britain reached a phenomenal production rate, which was a big factor in winning the war. A good manager should plan to simply follow and ask for help when required, and to lead and manage when required, and know the difference between these two.

Having a Plan B and Anticipation

Things go wrong for even the best of planners and foreseers. As engineers and designers we learn the importance of leaving room for failure, having safety mechanisms and fallback plans. Designing and running a firm or a project team is no different. Winners in the end are usually the ones with a Plan B, and even a Plan C, in case Plan A fails. The more alternative scenarios a leader can think of and the quicker the leader can identify the most likely ones, the better. Being an outsider-insider is helpful.

Managing and Leading Others

Any given leader is no more and no less than a representation of the collective efforts, combined talents and shared ambitions of coworkers. Thus, managing and leading other people is fundamental to success. As found through this research, a good leader displays three essential qualities:

1. One is getting to know your colleagues on a personal level with relationships based on respect.

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[5] Jenkins, Churchill: A Biography, 2001

2. Second, a good leader always gives the team full credit and accolades for all its successes. This credit ought to be made visible both in and outside the team. It wins unshakeable loyalty for the leader.

3. Third, a good leader is ready to take the blame for the team. If an effort or idea fails, a good leader takes responsibility as the bearer of the mantle. This shields the team from outside pressures and uncertainties. Then, using personal relationships and trust built within the team, a good leader coaches and advises those members whose shortcomings had cost the team its success. In general, making scapegoats of people and managing by fear simply does not work.

Top-down approaches simply do not work, and the insider-outsider framework is far likely to succeed. For each manager, the leadership story starts from the self and ends with others. Only insider-outsiders who understand their situation and soak up all the external help can bring about true change through leadership. It would take a lot to be an outsider-insider. Managers need to put my heart and mind into accepting and understanding the culture and needs of their surroundings. However, they need to make an active and continual effort to update their way of thinking and stay informed about best practices.

In the following section, other NA OEM-specific ideas to manage change for better product quality.

Short and long-term opportunities

Improvement plans at NA OEM can be viewed from a short and long-term lens. However, due to the challenging landscape of the automotive industry, while short-term implies no more than a few months, long-term would mean a couple of years or less.

Within product development (PD) cluster

Opportunities for short-term improvements include the creation of a REP (plant) System Engineer:

Objective: Vehicle level squeak and rattle, water leaks and wind noise are monitored by REPs using Manufacturing-issued procedures. TGWs, special studies, and component-level changes at the plant are not always traced back to system level attributes, in particular door closing efforts. Creating a system-level position for closures (primarily side doors) would help in upfront actions on issues with closing effort and attribute tradeoffs at an ongoing basis. In order to implement system engineering at REPs, PD's CSI provides a high-level model, and the PD CSE gives a direct interface with the REPs closures position.

Roles and Responsibilities:

- Take ultimate responsibility for door's wind noise, water leaks, S&R (squeak and rattle), closing efforts
- Support the door attribute target cascade to affected components within the door system boundary
- Develop system related solutions to meet attribute requirements fed back by warranty and PD
- Lead resolution of customer satisfaction issues post launch as required and capture learning achieved
- Develop and maintain roadmaps of compliance, best practice and quality improvement actions
- Support the development of the final door design and assembly strategy starting at prototype build
- Support launch team to ensure attribute targets are met, and fresh eyes related door issues are closed
- Learn the effect of design inputs on system performance and door sensitivity analysis*
- Understand door closing contribution analysis* to identify areas for changes (* available through PD)
- Understand all design guides and requirements pertaining to PD design inputs for closures attributes
- Facilitate communication with all parties: Variation Reduction Teams (REPs' VRT), PD, Mfg., body
- Follow DFSS (design for six sigma), PD/Mfg. studies on attributes; especially wind noise vs. effort

- Interface with Dimensional Control and Functional Engineering to approve door setting changes

- Participate and coordinate in meetings of REPs VRTs: wind noise, water leaks, S&R, sheet metal

- Focus on attribute compatibility/tradeoff first, data creation second, plan verification as final priority

- Ensure changes related to fit and finish/craftsmanship are compatible with system-level attribute needs

- Avoid deep diving into component issues if system-level issues or analyses are pending

- Maintain an updated contact list of suppliers, Mfg., PD and Process engineers relevant to door system

- Others: as deemed appropriate by supervisor and program needs, as long as system takes priority

Specific Actions:

1. ***Prototype Build*** – spend at least two weeks with PD, specifically at door assembly and teardowns. REPs' Supervisors and Manager should coordinate with PD counterparts
2. ***Launch*** – support PD CSE during trial builds, attend relevant meetings that discuss issues during launch, and participate in walkthroughs. Meet with PD CSE on weekly basis after trial builds
3. ***Production Life*** – document all knowledge gained by solving closures issues, share with program's PD CSE and CSI. Report desired changes to future design and current SDS requirements back to PD. The Manager of REPs will help elevate design issues to the right level

There are several other short-term opportunities, such as more organizational leverage to CSIs in PD and to assign at least half time manufacturing CSIs to programs. In the long-run, standardization of tasks suggested in chapter 6 and better knowledge management across programs ought to be the goals.

Between PD, stamping, suppliers and manufacturing

Starting in the short-term by leveraging the current CSI role in PD, NA OEM ought to create a formal simultaneous engineering organization centered in Manufacturing to coordinate between PD, stamping, and suppliers for better system attribute delivery.

Changing management decision processes

Both in the short-run and the long-run, management ought to revise its decision making to become more based on empirical data and inclusiveness of stakeholder feedback while minimizing interventions that derail current programs for the system focus.

Emphasis on data-driven cost-benefit analyses

For any special projects that take away from program man-hours, content changes in the name of changing customer needs in the middle of programs or externally-induced revisions of frozen tasks in the DSM, NA OEM is urged to utilize data-driven cost-benefit analyses. The general sentiment at the engineering level is that management does not understand the impact of changes and usually expects engineers to do project work of little value. This needs to be changed.

Using appropriate incentives and system metrics

As discussed before, NA OEM should introduce incentives that reward upfront system-level dexterity and task execution more than firefighting. This combined with other details in this chapter send a consistent message across for improvement in the firm.

The next chapters summarize the conclusions and recommendations of the overall research and its findings.

11. Outcomes and Results

This chapter presents a very concise summary of findings that have been laid out in earlier chapters. Some of these findings are observations and others come from data analysis. The two are distinguished in sections below, as much as possible.

Improving product quality

The strongest levers to improve NA OEM's product quality and attribute performance are:

- Steps that reduce individual task time (DSM)
- Prioritizing work on critical decisions or tasks (DSM)
- Mechanisms to reuse existing knowledge and prior experience (DSM)
- Frontloading the process for attribute tradeoffs, analyses and predictions (DSM)
- Developing tools required to address design parameter coupling and conflict that could compromise system-level performance (DSM and Observations)
- Clearly defining component interfaces and ownership, with methods for managing component interactions with multiple owners (DFC)
- Using a methodology for dimensional and assembly analysis that also enables communication of data in with trust and consistency (DFC and Observations)
- Minimizing the number of handoffs in the process (observations)
- Minimizing and isolating dimensional variations (observations)
- Elimination of non-essential tasks that shift process focus (observations)
- Organizational leverage for system engineering roles (observations)
- Well-defined system integration or simultaneous engineering roles (observations)
- Collective responsibility of stakeholders for attribute delivery (observation)
- Clearly defined incentives for contributing knowledge and organizational learning with a culture that rewards upstream excellence vs. firefighting (observation)

There are several other levers of PD process improvements that could be found in chapters 6 through 9. The following section discusses interface management needs.

Understanding key interfaces

Three types of interfaces are critical to manage in product development. There are as follows:

Organizational Interfaces

The ownership and control of door system attributes falls under different organizational clusters. There needs to be a clear decision-making authority and coordination steps for such organizational interfaces within the PD cluster. Cross-chimney clusters like manufacturing and PD need more coordination too.

Process Interfaces

Process interfaces are defined information exchange that occurs by handoffs in during the execution of the program. At NA OEM, a lot of work to make preliminary decisions is recreated because of loss of knowledge or credibility of data during handoffs (occurring in high numbers).

Component Interfaces

These interfaces are defined either by mechanical assembly requirements (constraint in the DFC) or information flow between tasks captured in the DSM. Some of the interfacing components are owned by the same team but not in general. There needs to be a system integrator who coordinates the component interfaces while accounting for system attributes.
Cross-chimney communication and task priorities
The Datum flow chain provides insights to the need of cross-chimney coordination. Following is a list of teams that need cross-functional communication with what type of information needs to be exchanged:
Between manufacturing and product development: Information exchange and coordination is needed for tasks related to locator schemes for assembly, ergonomic considerations and determining dimensional variation. The communication between PD and manufacturing is critical for many tasks. As one example, late changes in assembly decisions require costly and time-consuming revisions to sheet metal design.
Between stamping business unit and product development: tasks such as die draw angles, size of stamping radii and feasibility checks need coordination between stamping and product

development. These decisions need to be frozen as early as possible and changes ought to be avoided at all costs. In addition, redoing the same feasibility checks at different stages of the process is costly.

Between studio and product development: arguably the most critical task, namely the external surface design for door sheet metal, needs collaboration from PD and studio. Studio needs to account for manufacturing's opinions on assembly and stamping's opinion on sheet metal formability – aspects that the PD team can coordinate. Again, all the stakeholders ought to agree with the surface design details.

Between product development and plant teams: this communication needs to be more broad-based than the examples before because it entails a knowledge transfer between the PD cluster and (designated) assembly plant team. If the knowledge transfer about the product is complete, plant team is better positioned to handle dealership warranty complaints (as responsible for it).

Prioritization of design tasks

Critical design tasks are defined in three ways along with a list of tasks found from the DSM:

Tasks as inputs to critical system decisions: class1 surface, level of seals, door cheat, seal parameters (stiffness, dimensions, gaps), dimensional variation, seal gap capability and effort test

Changing the outputs of these tasks causes several iteration loops and more rework.

Process-time bottleneck tasks: stamping feasibility, welding feasibility, class 1 surface, any revisions to platform assumption, door stiffness predictions, assembly decisions (such as paint process, locator schemes), Most of the process-time bottlenecks also happen to be early decisions.

Information bottleneck tasks: door closing effort test, door closing effort prediction model, door cheat decision, door cheat prediction model, seal parameters (stiffness, dimensions, gap), margin and flushness targets (with allowable variations), seal gap variation studies. Most of the information-based bottlenecks happen to be prediction or dimensional tasks.

Identification of value-adding vs. non-critical PD Steps

As-is time spent – Engineers spend a fifth of their work time on the following categories in as-is PD: design parameters, physical testing, modeling analysis, manufacturing and assembly, reworking early decisions. Thus, the process is not front loaded because modeling and analysis (mostly done at concept or early PD stages) is not a clear priority. The fact that physical testing is given an equal amount of time also shows the reliance on prototypes to confirm designs, which sometimes leads to major design changes from downstream work. Changes to early decisions also take a significant time.

Special Projects: Several management-assigned tasks or special projects were observed at NA OEM. The value of such special projects is debatable. An example from one car program shows that for two (calendar) months, engineers were asked to perform a special benchmarking and target improvement study on margin and flushness, on which they spent about 90% of their time. This diverted their attention from balancing other attributes. However, there is a need for a holistic view of a PD process when it comes to such projects.

While these projects might affect resources for a given program, they do benefit the corporate target setting and market performance of the company as a whole, as long as the knowledge gained is shared across programs. Therefore, while the value of such projects might be debatable (as per the engineering team's view and not management's view), if a special project is deemed to be required then its impact on running specific programs must be actively managed. Better yet, the managers and engineers ought to be brought on the same page as to the value of such projects to the company's future. Ideally, such a project should be resources separately, but if it has to share key skills it must be done in a way as to understand the output implications in delaying some parts of the program completion that need to be dealt with separately.

As another example from a different program, the supplier for stamping was changed from external to in-house for cost savings. Because NA OEM's stamping requirements are different from external suppliers, 100% of work time during two calendar months was spent to redo the die draw feasibility. It was never determined whether this rework led to enough downstream issues from neglected tasks that neutralized all the cost benefits. Such decisions on actual programs should be frontloaded and away from the execution phase. If a business imperative does drive a change during execution, then the process plan should be recalibrated to the revised number of tasks that result – which could well mean adding time as well as resources depending on how lean the system is operating. [Pitts, 2007 Interviews]

We now summarize a couple of process-related approaches to improvement.

Approach for standards and holistic knowledge management

Standardizing as many tasks and design parameters as possible leads to several advantages. It is a significant enabler of completing all required design tasks. Standardization of critical tasks and commonly used components reduces lead-time to 50% of a process that does not use it. Better knowledge management can eliminate some of the interactions that need to be considered in all programs. This would mean capturing program experience and reasons behind design decisions in a centrally administered and continually updated knowledge base. The head-start enabled for certain tasks using the above could reduce the process lead-time by as much as 25%. The impact of both standardization and better knowledge management is shown through DSM simulations.

Managing technical and organizational complexity

Through the case study on side doors, the following tools are proven invaluable: DSM and DFC (technical and organizational insights), Others: Axiomatic Design (Technical), Insider-Outsider method (Organizational) Results from process simulations, once again, deserve a special mention for the insights they provide to managing technical and organizational complexity. Several improvement levers are tested and proven useful, including advantages of standardization, knowledge management and upfront analytical tools. In addition, an extensive organizational survey at NA OEM showed the importance of the system integrator role for coordination, and the need for more leverage and support for such roles. Gaps in coordination between PD and other clusters such as manufacturing and plant teams still exist. The next chapter summarizes some of the conclusions and recommendations from the project.

12. Conclusions and Recommendations

This chapter summarizes some of the main conclusions and recommendations from the case study on automotive product development. Most of the findings and suggestions are industry-neutral.

Approaches to system design and management

System design and process management requires conscientious balancing of conflicting customer attributes, minimization of revisions to decisions, coordination and information exchange across functions, and continuous organizational learning for improvements. Several analytical methods can be used (as shown by the findings below at NA OEM) to serve as tools that help in attribute delivery:

DSM: It is not possible to re-sequence the DSM to improve the order of task execution. The PD process for closures is a highly coupled one and needs attribute balancing right at the start. Simulation results show that the current process cannot finish in allotted process time and do all rework that arises. In addition, further improvements cannot come from doing each task faster. Instead, simulations prove that following levers are helpful to ensure task completion and delivery of system attributes: standardization and better knowledge management. Some attributes (such as noise) are favored by process sequence.

DFC: this captures relationships of geometric constraints, delivery of dimensional chains and Key Characteristics and cross-functional organizational interfaces for component assembly. As per the DFC results, teams deciding on KCs should consist of stakeholders influencing product quality. For closures, these include PD, Manufacturing and Stamping. In plants, KC flow down analysis should define the points measured by computerized measurement machines. Several examples of disagreements on dimensional data are observed between the PD and manufacturing groups. Consistently following the DFC and KC flow down approach will build trust in data. In addition, KCs management needs proper handoffs, especially between plant teams and PD. For this, the CSI is potentially a simultaneous engineer who can help with interface management

Organizational aspects

It has been observed that some attributes are favored by organizational structure (for instance wind noise). The ownership and control of system-level attributes such as closing effort can also be ambiguous. At the same time, coordination between manufacturing and PD is weak. CSIs (closures system integrators), who serve as links between different attribute reporting chains, improve attribute delivery and reduce design based rework. However, the roles and responsibilities of the CSIs are still not clearly defined. More often than not, the CSIs lack the necessary time and resources to help develop design guides and standards. In addition, CSIs end up taking part in design and release activities for components, which are far from the ideal focus on system attributes.

System Dynamics and Change Management

Analysis of resource utilization shows that NA OEM's closures PD is already spending over 81% of work time on task execution only (excluding any documentation or special projects). This is beyond the tipping point of firefighting whereby a small perturbation in the PD process would push the system to instability and continual catch-up. In addition, it is typical for management to assign special projects to engineers that take away from process focus. Occasionally the value of such projects to product quality is unclear. If such interventions that affect project resources cannot be avoided, they must be made as early as possible. In addition, such changes or projects should be communicated across the PD organizations and its interfacing cross-functional teams so that everyone understands the causal factor of the rework task which must be completed. As a result of this project's analysis, reduction of management intervention and avoidance of late program changes are desirable. NA OEM's System-aware resources also need to be expanded beyond the closures cluster. To manage such a change, an insider outsider approach that brings fresh perspectives and new knowledge inside NA OEM while leveraging the strong points of the existing culture is necessary. The next sections summarize few key recommendations.

Technical changes to product development

Improvements are needed in knowledge management at NA OEM, for which the DSM can help. Design specifications need to be improved to base targets on more statistically significant data samples and direct customer input. Also, methods on how to execute design and lessons from prior programs need to be captured in such guides. More resources are needed for benchmarking, which is lacking at NA OEM. There is a need to reduce over-reliance on testing that inherently builds in rework loops in the process. As one solution, better analytical tools and equations, especially for closing effort, and attribute tradeoff software should be developed to make the decision process frontloaded and reliable. Such tools would also enable equal weight for noise and effort attributes. There also needs to be a general shift from component to system engineering. NA OEM needs to increase PD's focus on systems and attributes delivered. Helpful steps would include greater use and improvement of standalone prediction tools such as for door closing effort. Similarly, more thorough and coordinated upfront analysis of stamping or assembly line ergonomics would prevent rework during launch. Certain types of system analyses could be implemented through the computer-aided design teams, for instance variation and door setting analysis based on the DFC or running the closing effort tool.

More standardization is needed in design and manufacturing in order to complete all tasks required to deliver a quality product that meets customers; expectations on attribute performance. For instance, following inputs need standardization: Stamping and operations feasibility analysis, Welding feasibility, Door hardware (hinges/check/latch) – *some of this is being done currently*, Dimensional strategy: seal gaps, cheat (or use no cheat), Also, in order to keep the process on track, zero to minimal intervention should occur for critical tasks or bottlenecks (discussed in previous chapter).

Organizational changes to system management

Building and retaining engineering knowledge can be a challenge at NA OEM where most engineers change job types in less than two years within the company. Therefore, increased tenure time (of system engineers in particular) would help with continuity. Similarly, more organizational leverage and focus is needed for the CSIs who are some times unable to implement decisions that benefit the system as a whole although performance on certain components might slightly be compromised. For instance, managers can lend more credibility to the CSI role by attending their weekly meetings and forums more regularly, and facilitating system balancing.

The CSI is a single point of contact but system-level thinking needs to be specifically incentivized across the organization. To implement such organizational changes, NA OEM's approach needs more high level leadership committed to change for improvements. Managers have to formulate clear goals for system prioritization, and lead their teams consistently with a coherent message. As *insiders* to NA OEM, the managers know the firm's values, past history, and future ambitions. In addition, managers need to have the skill to identify the firm's weaknesses, yet keep growing and evolving by adopting external perspectives, good practices and proven methodologies as *outsiders*. Without realizing the importance of being *outsider-insiders* to their teams, it would be hard for managers to lead others.

Apart from the above, the credibility of manufacturing in PD is not strong and the involvement of manufacturing is not strong, persistent, or consistent. Manufacturing's ability to contribute needs to be strengthened. Decision processes should be updated so that manufacturing has a strong (or equal) voice and organizational alignment with PD. Also in general, better interface management (with the help of the DFC) and better coordination between PD-Manufacturing-Stamping-Plants is needed, in which management needs to be active as well. CSIs should continue playing critical role in: cross-chimney integration (Mfg.-PD-REPs), system level tradeoffs of attributes, tool/model development and integration, standardization of methods, documentation of guides and knowledge along with benchmarking (with technical specialists' support), and helping create plant Closures System Engineer role. However, improvements in the definition of CSI roles, responsibilities and expectations from management are needed. Details on organizational improvements are found in chapters 8 – 10. We now end the chapter and the thesis with some ideas for future research in closures and PD.

Ideas for Further Research.

There are several interesting areas of research that could be investigated to enhance the knowledge and practice of PD process execution. Some ideas related and as follow-up to this study are suggested. The work done in this study using the DSM and DFC can be further expanded. Developing a DSM for a best-in-class OEM and running simulations would lead to further insights. Also, performing variation analysis on seal gaps using the DFC can be used to double check the results from variation simulations performed by manufacturing. Tools for attribute prediction deserve special attention. Closing effort is on top of the list when it comes to closures. In addition, studies on trend-setting doors in assembly plants using DFC-based methods without needing physical vehicle would help deliver robust design and assembly scheme. For firms as NA OEM that face several constraints, the idea of building human resources based on flexible capacity could be a useful one. Investigating the possibility of training personnel so that they can move from one cluster to another as needed could help. Another novel area of research would be studio design. The ability to affect and predict surface styling trends could lead to a competitive edge for the automotive industry. It would also enable more confidence in design and fewer changes. Similarly, research on tradeoffs between new product sales from flexible surface design (sales from coming out with all-new exterior surfaces) and cost savings from more standardization (minimizing changes to stamped parts from existing to new programs) could also lead to useful results for the automotive sector. The benefit of greater process speed to design tools and build at production volume as a business lever is also worth investigating.

Project appraisal methods for special studies that utilize program resources would help managers prioritize how they allocate resources. A cost-benefit framework for informed decisions on shifts in program focus can reduce the perception of management by sub-optimal approaches.

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Appendix 1

1). Following is a description of the files that are included.

The .csv Excel files are the base data files to create the DSM: the dsm.csv is the basic DSM; the dur.csv is the best, mean, and worst durations for each task (uses a triangular distribution in the simulation), the lc.csv is the learning effect for each task, and prob.csv is the probability or rework, volatility (likelihood of change on a scale of 1 – 10 if other tasks that feed information to this task also change, and sensitivity (impact on other tasks that receive information from this task if it is changed) for each task.
The way information is stored in the DSM is as follows:
Pane #1: Main DSM - access this in Matlab with DSM (:,:,1)
Pane #2: Probabilities of rework - DSM (:,:,2)
Pane #3: Volatility * sensitivity - DSM (:,:,3)
Pane #4: Standard deviations - DSM (:,:,4)
The core of the simulation is generating the initial task times from a triangular distribution, tracking the work as it progresses, and generating rework as appropriate based on the probabilities. Tasks start working when their upstream precedents are complete, and work until their "work remaining" is zero. It is possible to watch the aggregate work remaining decline by un-commenting line 50 of the simulation.

```
2). dsmoptimize.m
function [Best]=dsmoptimize(DSM,threshold)

Best=[];
i=1;
Lmax=0;
[frontorder,midorder,backorder,order,midoverlap]=dsmorderbasic(DSM);

%determine if midorder segments need to be rehashed to meet threshold
while i<=size(midorder,1)
  if sum(midorder(i,:)>0)>1
    midtemp=midorder(i,[find(midorder(i,:)>0)]);
    SubDSM=DSM(midtemp,midtemp,1);

    for j=1:size(Best,1)
        if not(isempty(find(midtemp==Best(j,1))))
            SubDSM(find(midtemp==Best(j,1)),find(midtemp==Best(j,2)))=0;
        end
    end

    for j=1:size(SubDSM,2)
        SubDSM(j,j)=0;
    end

    if max(eig(SubDSM))>threshold
        [SubDSM,best]=dsmtear(SubDSM);
        Best=[Best;midtemp(best(1,1)) midtemp(best(1,2)) best(1,3)
best(1,4)];
        [forder,morder,border,oorder,mo]=dsmorderbasic(SubDSM);
```

```
        start=find(order==midtemp(1,1));
        stop=find(order==midtemp(1,length(midtemp)));
        order(start:stop)=midtemp(oorder);

        midorder(i,[find(midorder(i,:)>0)])=0;

        for j=1:size(forder,1)
            n=size(forder,2);

frontorder(end+1,[find(forder(j,:)>0)])=midtemp([forder(j,[find(forder(j,:
)>0)])]);
        end
        for j=1:size(morder,1)
            n=size(morder,2);

midorder(end+1,[find(morder(j,:)>0)])=midtemp([morder(j,[find(morder(j,:)>
0)])]);
        end
        for j=1:size(border,1)
            n=size(border,2);

backorder(end+1,[find(border(j,:)>0)])=midtemp([border(j,[find(border(j,:)
>0)])]);
        end

    end

  end
  i=i+1;
end

%dsmmode
```

3). dsmorderbasic.m

```
function [front,middle,back,order,overlaps]=dsmorderbasic(DSM)

A=DSM(:,:,1);
n=size(DSM,2);
for i=1:n
    A(i,i)=0;
end

order=[1:n];
front=zeros(1,n);
fr=1;
frplace=1;
back=zeros(1,n);
ba=1;
baplace=n;
middle=zeros(1,n);
mi=1;

while isempty(order)==0;

%move rows out, then columns out
for type=2:-1:1
while sum(sum(A,type)==0)~=0
```

```
    [so,si]=sort(sum(A,type)==0);
    switch type
        case 2
            front(fr,frplace:frplace+size(order(si(so==1)),2)-
1)=order(si(so==1));
            frplace=frplace+size(order(si(so==1)),2);
            fr=fr+1;
        case 1
            back(ba,baplace-
size(order(si(so==1)),2)+1:baplace)=order(si(so==1));
            baplace=baplace-size(order(si(so==1)),2);
            ba=ba+1;
    end
    order=order(si(so==0));
    A=A(si(so==0),si(so==0));
end
end

%pull first middle task and its associates out
R=A;
m=size(R,2);
for i=1:m
    R(i,i)=1;
end

R=R^m;
for i=1:m
    row=R(i,:)>0;
    col=(R(:,i)>0)';
    if row.*col==row
        [so,si]=sort(row.*order);
        middle(mi,frplace:frplace+size(so(so>0),2)-1)=so(so>0);
        mi=mi+1;
        frplace=frplace+size(so(so>0),2);
        order=setdiff(order,so(so>0));
        break
    end
end

if isempty(R)==0
    A=A(setdiff(1:m,[1:m].*row),setdiff(1:m,[1:m].*row));
end

end

order=sum([front;middle;back],1);

index=1;
M=DSM(order,order,1);
for i=1:size(M,1)
    last=i;
    for j=i:size(M,2)
        if M(i,j)>0
            last=j;
        end
    end
    if last>i
```

```
            overlaps(index,i:last)=order([i:last]);
            index=index+1;
        end
    end

    if exist('overlaps')==1
    for i=1:size(overlaps,1)
        for j=i+1:size(overlaps,1)
            check=overlaps(i,:)-overlaps(j,:);
            if sum(check==0)>sum(overlaps(i,:)==0) & sum(check<0)==0
                overlaps(j,:)=0;
            end
        end
    end
    else
        overlaps=[];
    end
```

4). Dsmsimulatejehan.m (note that input files are hard coded - names have to be changed)

```
function
[WorkTimes,WorkPath,minimum,logavg,logsd]=dsmsimulatejehan(DSM,TriDur,LC,m
axruns,order)

n=size(DSM,2);

%DSM panes are:
%1: Average durations and combined prob*impact
%2: Probabilities
%3: Impacts
%4: Standard deviations

% reorder all matrices before starting runs
DSM=DSM([order],[order],:);
LC=LC([order],:);
DSMTemp=DSM;
run=0;

% loop starts here
while run < maxruns
    DSM=DSMTemp;
    run=run+1
    increment=1;
    time=0;

    %sample durations from triangular distribution if not reduced,
lognormal if reduced
    for i=1:n
        if imag(DSM(i,i,4))==0
            DSM(i,i,1)=tripdf(TriDur(i,1),TriDur(i,2),TriDur(i,3));
        else

DSM(i,i,1)=imag(DSM(i,i,4))+lognrnd(DSM(i,i,1),real(DSM(i,i,4))); %minimum
plus lognormal of difference
        end
        for j=1:n
            if DSM(i,j,2)~=0
```

```
                DSM(i,j,2)=tripdf(max(DSM(i,j,2)-
DSM(i,j,4),0),DSM(i,j,2),min(1,DSM(i,j,2)+DSM(i,j,4))); %probabilities
                DSM(i,j,3)=tripdf(max(DSM(i,j,3)-
DSM(i,j,4),0),DSM(i,j,3),min(1,DSM(i,j,3)+DSM(i,j,4))); %impacts
            end
        end
    end

    TaskDist=diag(DSM(:,:,1));

    %initialize work variables and storage
    WorkRemaining=TaskDist;
    WorkedYet=zeros(n,1);
    WorkPath(1:n,increment,run)=WorkRemaining;
    WorkPath(n+1,increment,run)=time;

    %begin execution of run loop
    while sum(WorkRemaining>0)

        sum(WorkRemaining>0) %show output to convergence (comment out to
turn off)

        %figure out what can be worked now (if there's work to do and
*upstream* precedents are complete)
        WorkNow=zeros(n,1);
        for i=1:n
            WorkNow(i,1)=WorkRemaining(i,1)>0 & (sum(WorkRemaining(1:i-
1,1)'.*DSM(i,1:i-1,2))==0);
            WorkedYet(i,1)=WorkedYet(i,1)+WorkNow(i,1);
        end

        %process work in time step (just subtract the time)
        WorkInProgress=WorkRemaining.*WorkNow;
        timestep=min(WorkInProgress(WorkInProgress~=0));
        WorkRemaining=max(0,WorkRemaining-timestep*WorkNow);

        %if just finished in this round, add to dependency work (if
probability satisfied, has been worked already, include learning and
impact effects), not sampling for added rework duration
        for i=1:n
            if WorkRemaining(i,1)==0 & WorkNow(i,1)==1

WorkRemaining=WorkRemaining+(rand(n,1)<DSM(:,i,2)).*(WorkedYet>0).*LC.*DSM
(:,i,3).*TaskDist;
            end
        end

        %advance and output results at new time
        time=time+timestep;
        increment=increment+1;
        WorkPath(1:n,increment,run)=WorkRemaining;
        WorkPath(n+1,increment,run)=time;
        WorkTimes(run)=time;

    end
end
```

```
%hist(WorkTimes,100)
minimum=min(WorkTimes);
logavg=mean(log(WorkTimes-min(WorkTimes)*ones(1,size(WorkTimes,2))+.001));
logsd=std(log(WorkTimes-min(WorkTimes)*ones(1,size(WorkTimes,2))+.001));
```

5). dsmtear.m

```
% Routine to find best interaction to tear and remove it
function [DSM,tear]=dsmtear(DSM);

A=DSM(:,:,1);
n=size(A,2);

for i=1:n
    A(i,i)=0;
end

[s,v]=eig(A);
tear(1,3)=max(real(diag(v)));
maxeigcols=find(real(diag(v))==max(real(diag(v)))); %get max eigenvalue
columns
[y,indices]=max(abs(s(:,maxeigcols'))); %indices of tasks with most work
(weight here by time or cost???)

%build possible interactions list
M=zeros(n);
for z=1:size(indices,1)
    M(indices(z),:)=1;
    M(:,indices(z))=1;
end
[i,j]=find(M.*A>0);

 %find best index to remove
for z=1:length(i)
    temp=A(i(z),j(z));
    A(i(z),j(z))=0;
    L(z)=max(real(eig(A)));
    A(i(z),j(z))=temp;
end

%store and zero the torn interaction...
[Lorder,Lindex]=sort(L);
tear(1,1)=i(Lindex(1));
tear(1,2)=j(Lindex(1));
tear(1,4)=Lorder(1);
DSM(i(Lindex(1)),j(Lindex(1)),1)=0;
```

6). jehan.m (creates input files)

```
DSM(:,:,1)=csvread('jehandsm.csv'); %read in base DSM
TriDur=csvread('jehandur.csv'); % read in durations for each task to an
array (used in simulation)

for i=1:size(DSM,2)
    DSM(i,i,1)=TriDur(i,2); %store mean duration on diagonal.
end

LC=csvread('jehanlc.csv'); %read in learning effects
Prob=csvread('jehanprob.csv'); % read in base probabilities
```

```
% fill in rest of DSM
for i=1:size(DSM,1)
    for j=1:size(DSM,2)
        if i~=j
            if DSM(i,j,1)~=0
                DSM(i,j,1)=Prob(j,1)*Prob(j,2)*Prob(j,3); %combined
interaction value in pane #1
                DSM(i,j,2)=Prob(j,1); % probabilities of rework in pane #2
                DSM(i,j,3)=Prob(j,2)*Prob(j,3); %impact / sensitivity in
pane #3
            end
        end
    end
end

DSM(:,:,4)=zeros(size(DSM,2)); %give zeros to all of the standard
deviations in pane #4
```

7). tripdf.m (triangular distribution generator)

```
function [sample]=tripdf(a,b,c)

y = rand;
sample = a + (y * (b - a) * (c - a))^0.5;
if sample > b
   sample = c - ((1 - y) * (c - a) * (c - b))^0.5;
end
```

[McGill, 2005]