Complexity Reduction in Automotive Design and Development

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Abstract

Automobiles are complex products. High product complexity drives high levels of design and process complexity and complicatedness. This thesis attempts to reduce complicatedness in the automotive vehicle design and development process utilizing systems engineering tools including the design structure matrix (DSM) and axiomatic design concepts. The title of the thesis is a misnomer; complexity in automotive design and development is not "going away", but through the use of system engineering tools it is believed that the complicatedness of automotive design can be reduced and the consequences of decisions can be better understood at earlier stages in product development. A holistic view of the complexity and complicatedness challenge is considered, in order to identify high leverage points and generic insights that can be carried forward to future product development efforts. The goal is to translate generalized learning and systems thinking to the application of systems tools and processes that enable an understanding of complexity, in order to design better operating policies that guide positive change in systems.

The analysis starts with considerations across the automotive enterprise, then the focus sharpens to the early stages of the product development process. Then a more detailed level of abstraction is considered when the automotive chassis tuning process and the interactions between the vehicle dynamics and noise and vibration (NVH) attributes are considered. The automotive rear suspension design is used to illustrate the concepts at the detailed level of abstraction. A rear suspension system case study is included, as it met a number of the challenges inherent in large-scale systems; it provides the elements of a technical challenge and the integration of business and engineering issues, while encompassing detailed and broad issues that across different parts of the organization.

The analysis demonstrates that the complicatedness of systems can be reduced and complexity can be managed through the use of the design structure matrix and axiomatic design concepts. Recommendations are made to foster improved decision-making that will result in improved automobiles and include the following: start simply with the application of these concepts on the critical few interactions that drive system performance, manage information explicitly, account and provision for risks in the development process, and reduce complexity and complicatedness through reuse.

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Acknowledgements

I would like to thank Ford Motor Company management for their support throughout the System Design and Management Program. I would also like to thank my student cohort, professors, and SDM administration – their dedication, enthusiasm and contributions made the journey a pleasure. Thank you Dan Whitney for your guidance and feedback during the development of this thesis. Finally, I would like to extend a special thanks to my family and friends for their support, encouragement, patience, and understanding over the last two years.

This effort is dedicated to my parents, who have exhibited great courage in the face of significant challenges over the past year. Finally, to my future wife Jenny – you have made the last year the best of my life.

Ronald Ziegler
January 2005

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Automobile Complexity and Complicatedness

Automobile product complexity drives high levels of design and process complexity and complicatedness. Complexity leads to challenges within and between technical, organizational/ human, and process domains. Merriam Webster delineates the difference between complex and complicated as follows: complexity "suggests the unavoidable result of a necessary combining," while complicated "applies to what offers great difficulty in understanding, solving, or explaining." Complexity involves systems, while complicatedness involves the human condition. This thesis attempts to reduce complicatedness in the automotive vehicle design and development process utilizing systems engineering tools including the design structure matrix (DSM) and axiomatic design concepts. Through the use of system engineering tools it is believed that the complicatedness of automotive design can be reduced and consequences of decisions can be better understood at earlier stages in product development. The scope of the thesis, thesis problem statement, and framework used to address the challenge of automotive design and development are summarized in this chapter. Finally, the layout of the remainder of the paper is described.

Scope

A holistic view of the complexity and complicatedness challenge is considered, in an effort to identify high leverage points and generic insights that can be carried forward to future vehicle programs. The goal is to move from generalized learning and systems thinking to the application of systems tools and processes that enable an understanding of complexity and the design better operating policies to guide change in systems. The analysis starts with considerations across the automotive enterprise, then the focus sharpens to the early stages of the product development process. Then a more detailed level of abstraction is considered when the automotive chassis tuning process and the interactions between the vehicle dynamics and noise and vibration (NVH) attributes are considered. The automotive rear suspension design is used to illustrate the concepts at the detailed level of abstraction.

Approach

Complexity and complicatedness are interdisciplinary challenges. For this reason, issues in the organizational/human, process, and technical domains are considered. The organizational/human domain deals with the human behavior in complex systems, where the relationships are governed by human capabilities and relationships. The process domain deals with the decomposition and execution of tasks, where the relationships are governed by information flows, timing, and methods. The technical domain deals with the functional aspects of automotive design, where the relationships are governed by physics.

Case Study: Rear Suspension System

The following case study introduces the decision-making challenges involved in the selection of the proper rear suspension system architecture for an automobile. The case study was selected as it met a number of the challenges inherent in large-scale systems; it provides the elements of a technical challenge and the integration of business and engineering issues, while encompassing detailed and broad issues that across different parts of the organization. The case study was selected for its relevance and appropriateness in demonstrating the concepts presented herein and is not intended to be a judgment of the decisions and performance of the team involved in the case. The case study provides an example of the human, process, and technical challenges involved in automotive complexity and complicatedness.

The Issue

A vehicle program was not meeting aggressive cost targets at the Program Approval, <PA> gateway. In order to proceed through the gateway and continue with the program, the team was presented with a number of difficult choices. The program assumptions were reviewed in order to identify cost-saving opportunities. One of the cost-saving opportunities under consideration was the rear suspension system. The team was asked to reconsider the rear suspension architecture selection and consider an alternate, low-cost design. During the early pre- <PA> stages of the program the independent rear suspension (IRS) architecture type was selected due to the many functional benefits it provided over the outgoing solid axle-type rear suspension system in the prior vehicle model. Prototype vehicles were made with the IRS and initial chassis tuning and development was completed in order to demonstrate that functional target ranges could be achieved. Initial cost estimates for an alternate 3-link type solid axle system indicated sufficient cost savings to allow the program to meet cost targets.

The Decision

Chief Engineers and Engineering directors from Vehicle Engineering, Chassis Engineering, Finance and Vice Presidents of the company were involved in the suspension architecture decision. The leadership team was initially split with respect to the rear architecture change proposal. Vehicle program management and the chassis organization desired the more sophisticated IRS, while finance built the case for and supported the solid axle architecture. The Vice Presidents eventually made the call for the solid axle architecture based on the information available at the time. The decision was made. Management released a one-page document to the team stating the necessity for tough decisions; to achieve the target return on investment and continue segment domination, significant cost and weight reduction was required. In addition, there was a strong desire to hold the Job <1> production timing. Additional resources were allocated to hold the timing. Shortly after the decision, the program Chief Engineer and Chassis Chief Engineer were reassigned. While this thesis does not presume a cause and effect relationship between the rear architecture decision and the reassignments, one could infer that the chassis architecture change was a factor in the organizational changes.

The Task

The team was tasked to develop the new rear architecture in just over four weeks – a monumental mandate given that a new architecture development can typically take months to complete. The task was led by the Package Engineering group, where the focus was making the new system fit while minimizing the change required to other systems such as the body structure. There was very little input from the functional attributes at this stage, due in part to unfamiliarity with the new system and lack of presence in the decision-making process. Neither formal functional targets nor target cascades were used. There was also a strong push to reuse components of a solid axle system from an existing company vehicle line. While the new concept "boxed", i.e. brought financial performance back to target, challenges loomed.

Unanticipated Factors

As the system evolved, it became clear that a number of the parts could not be reused as originally planned. Additionally, other systems in the vehicle were impacted and would require more changes than originally thought. These factors drove increases in the cost of the new, solid axle system. Risk was high, as the impact on the functional attributes was not understood due to the lack of involvement of the proper technical subject matter experts in the decision and the lack of prototypes needed to demonstrate the new system performance. In particular, the robustness to Noise/Vibration/ Harshness (NVH) attributes such as axle and road noise was not quantified. Additionally, the tunable parameters that influence vehicle steering/handling and NVH, such as rubber bushing mount stiffness, were not established.

The Organization

The Vehicle Engineering organization was responsible for delivering overall vehicle performance. The team was organized with the engineers reporting to their functional and attribute managers. The functional and attribute managers controlled the headcount and budget. The engineers did not have a direct reporting relationship with the Vehicle Engineering Manager. This arrangement did not foster tradeoffs between the attributes, as attribute managers were tasked to deliver their attributes, and not overall vehicle performance. Accountability and responsibility for individual attribute performance were aligned, but at the cost of compromising the tradeoff mechanisms between attributes due to the lack of organizational power and resources afforded to the Vehicle Engineering Manager. Once the vehicle architecture is selected, the parameters that are available to optimize are limited and involve multiple stakeholders. In this case the two architectures under consideration affect the level of interaction between vehicle dynamic and NVH attributes in significantly different ways. A description of the attributes and parameters involved and the differences in the interactions for the two suspension types will be considered in later chapters.

Prototype Development

Prototype vehicles were received extremely late relative to the typical product development cycle, and were in short supply. A schedule was developed to share the vehicles. Testing was scheduled and conducted around the clock; engineers were asked to work at all hours of the day. The early prototypes highlighted significant technical challenges in terms of vehicle dynamics and noise and vibration attributes. Axle noise levels were extremely high, and the solid axle system did not provide the level of handling control and ride comfort that is apparent in IRS systems. The NVH and Vehicle Dynamics teams worked independently to achieve their attribute performance. The NVH focus was on the development of the appropriate countermeasures to mitigate axle noise. The Vehicle Dynamic focus was on tuning the chassis in order to improve steering and handling without trading off ride comfort. One of the NVH countermeasures to improve vehicle robustness to axle noise was the use of softer rubber isolators in the rear suspension system. This countermeasure was not adopted due to the adverse effects on the vehicle dynamics including steering and handling performance.

Team Dynamic

Much of the management effort was focused on the axle performance, with the belief that if the axle source vibration levels could be reduced, fewer actions would have to be adopted at the vehicle level. A team was stationed at the axle supplier's site to work to reduce the vibration levels of the axle and variation in axle vibration performance. Frustrations arose as the team struggled with the significant technical challenge. The axle team believed significant improvements could me made at the vehicle level to reduce their challenge, while the vehicle team was frustrated with the level of variation in axle vibration and the lack of ability to mitigate the vibration at the source. This led to resentment between the two teams. At the center of the teams' frustrations and the root-cause for many of the issues was the great challenge of placing a solid-axle type system in a uni-body type vehicle. The solid axle architecture is not typically used in vehicles with a uni-body construction (i.e. no frame), but rather in truck applications, where there is a frame that provides another level of isolation from the chassis via body mounts.

The Result

Each team developed and implemented changes and refinements to the 3-link solid axle chassis system that resulted in significant improvements in both NVH and vehicle dynamic attribute performance. The subsequent release of the vehicle to the media provided positive reviews for the vehicle dynamic performance. A number of countermeasures were added to improve NVH performance. This led to significant additions to the cost and weight of the system late in the program development. The cost of these late changes was not anticipated, nor factored into the initial rear chassis architecture decision. The ultimate question of whether the proper decision was made remains to be seen and will be based on sales performance, quality performance, and a complete post-release cost analysis.

Relevance to the Thesis

The case study illustrates the challenges in automotive design and development and highlights the significance of having a fundamental understanding of systems and interactions within systems early in the product development process. The thesis offers the design structure matrix and axiomatic design concepts as systems engineering tools that can be used to prevent such problems in the future. Methods such as the design structure matrix and axiomatic design concepts allow the engineer and manager to ability to identify interactions and tradeoffs early in the product development process and make more informed decisions. This case highlights a component/hardware – centric approach as apposed to a functionally cascaded-systems approach to automotive design. This has significance in the way decisions get made and in the way the teams are organized.

Problem Statement

Organizational/Human Challenge

Complexity is apparent at many levels of abstraction in the automotive industry. The thesis considers the organizational and individual challenges at both the enterprise level and at the specific design decision level. At the higher levels of decision-making, challenges including selecting the proper vehicle attribute balance and final design from among many alternatives. Decisions must be made in an environment where knowledge of the impact of such decisions is not always completely understood.

Complex decisions also exist at the lower levels of abstraction. The case of the rear chassis design as it relates to noise and vibration and vehicle dynamics is considered. At the lowest level of abstraction, task complexity is high for both the vehicle dynamics and NVH engineer. It is typical for engineers working on each attribute to stay in the chosen functional area for most of their careers, with few engineers making the transition between the two attributes. This results in a limited base of engineers knowledgeable in both attributes. The vehicle dynamics engineer selects design parameters that have a significant effect on NVH performance, while the NVH engineer sets targets that impact the vehicle dynamics performance. This challenge highlights the benefits of developing managers with knowledge of both attributes in greater depth. In this way, a balance between breadth (Managers) and depth (Engineers) of knowledge is achieved in the organization. This is not unlike Toyota, where managers are trained to understand multiple systems in great depth, while keeping engineers in one functional area or two.

Process Challenge

The process to convert an idea to an automobile presents many challenges. How an automotive manufacturer structures and executes internal processes can have significant effects on differentiation and success in the marketplace. The process challenge is considered at the Enterprise level in the analysis. At the lower level, the process challenges relating to the current design and development process for a chassis design is considered.

Technical Challenge

Complexity in the technical domain is considered in the analysis of the decisions involved in the automobile chassis design and development. A framework for managing the complex system interactions is presented using Axiomatic Design concepts in the assessment of a chassis system architecture.

Thesis Structure

The remainder of the thesis is organized as follows: Chapter 2 provides a characterization of the automotive industry and highlights a number of the external and internal challenges of automobile design and development. Chapter 3 introduces terminology related to automobiles and attributes and highlights relevant literature influential in thesis development. Chapter 4 provides a review of the methods used in the thesis, including a description of the Design Structure Matrix (DSM) and Axiomatic Design concepts. Chapter 5 provides a summary and analysis of how complexity can be communicated and managed using the DSMs at the Enterprise, Pre-Program, and chassis-tuning levels of abstraction. Chapter 6 demonstrates how design can be improved through the application of axiomatic design concepts. Finally, chapter 7 summarizes conclusions and recommendations from the analyses and highlights opportunities for further study.

Introduction

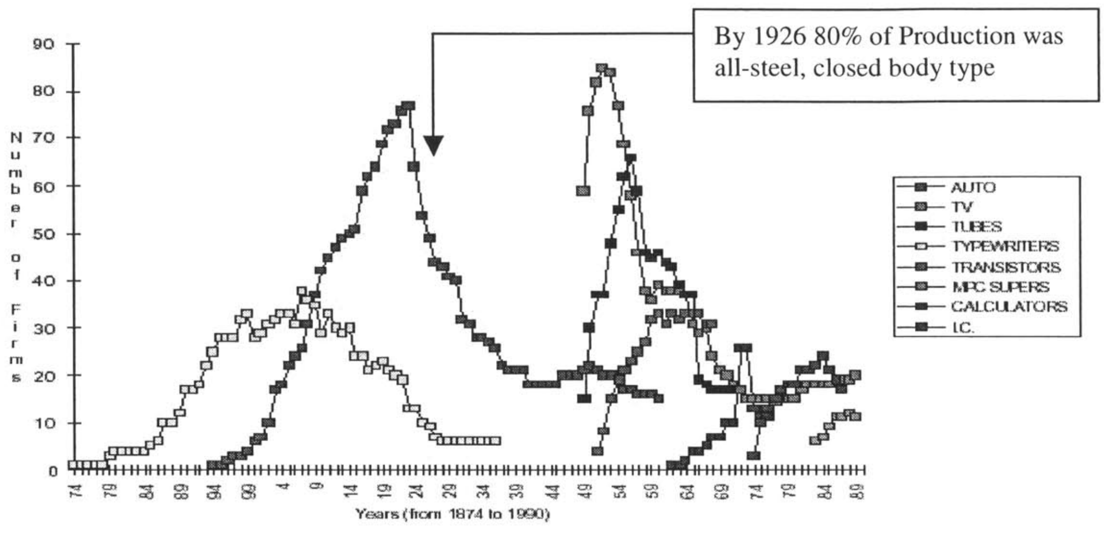
This chapter characterizes the nature of the automobile industry and highlights a number of the challenges involved in automotive design and development at Ford Motor Company. First, aspects of the industry are considered, and then the complexity of automotive design is discussed. A separate section is devoted to an analysis of dynamic complexity and how it manifests in the auto industry. Then Ford's development process is reviewed. A discussion of the significance of decisions that are made in the early stages of development and the impact of late design changes is then presented. Finally, a discussion of the approaches used to support decision-making at Ford is reviewed.

Automotive Industry

Dominant Design

The automotive industry is a mature industry. Ford Motor Company has been producing automobiles for more than 100 years. Utterback makes the connection between technological change and industry structure.[1] He illustrates that once the dominant design is established, the number of competing firms declines, and process innovation replaces technology innovation as the key differentiator among firms. In the case of the automobile, the adoption of the internal combustion engine and the coach style, all-steel closed body architecture in the 1920's established the dominant design. Figure 1 summarizes the number of firms in various industries as a function of time to reinforce the connection between the establishment of the dominant design and industry structure. Evidence supports this model, whether one considers the dominant designs of the QWERTY keyboard in the typewriter industry or the integrated circuit in the calculator market.

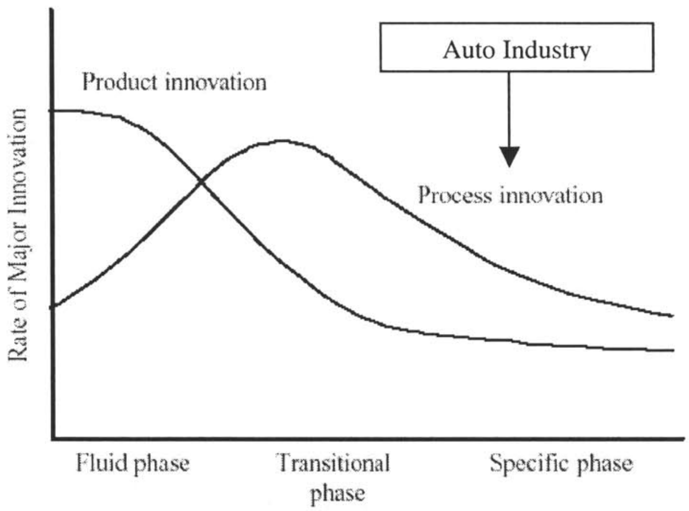
Figure 1. Dominant Design and Industry Structure[2]



Process Innovation

As the Automobile Industry has evolved, the shift to process innovation is apparent. This occurs as the emphasis has shifted from innovation to control through structure, goals, and rules. Major innovations are less apparent as the product development process focus shifts to more continuous, incremental changes in design. This has manifested in the incorporation of flexible manufacturing to allow shorter product runs to adapt to customers' changing needs and Lean Manufacturing and the Lean Enterprise to drive waste out of the enterprise. Flexible manufacturing and lean production techniques are well understood and practiced; Lean Enterprise initiatives are in the formative stages. In this mature industry, process innovation is a key differentiator between success and failure. Figure 2 shows the model of the general nature of product and process innovation.

Figure 2. General Phases of Product and Process Innovation.[3]



Cost and Timing

Ford Motor Company has been undergoing year-over-year billion dollar cost reduction efforts for more than five years. In that time, the company has continued to lose market share. Ford Motor Company's financial performance has been lower than the industry average, with net financial losses and the subsequent downgrading of the Company's credit rating. The Company has focused on driving costs out of the product and process in order to improve cash flows and achieve profitability. Another key to profits is shorter development cycles, which allow the opportunity to meet shifts in market demands with the right product. There is great pressure to maintain program timing and production schedules. Delays to program timing can result in opportunity costs of lost sales. There is also a high level of media attention on program launches; delays can result in negative media coverage. The strategic importance of timing is clearly illustrated in the Ford Motor Company business model. The goal is to "go simple, go common, go fast. Take decisions and execute, execute, execute!" The emphasis is to improve quality while simplifying processes to go fast. With the emphasis on speed the importance of making the right decisions becomes more significant in order to minimize rework, late changes, quality issues, and unnecessary costs and delays. Figure 3 below illustrates the "Back to the Basics" strategy.

Figure 3. Ford Motor Company "Back to Basics" Strategy.

Automotive Market

Competition

Automotive competition is increasing in all markets. The Sport Utility segment alone has grown from three entrants to more than sixty (60) (source: Automotive News). There is also an increasing number of manufacturers that are competing across national boundaries. This competition for market share is fierce. In the U.S. market, light vehicle sales have dropped 1% from 2002 to 2003 (Source: Automotive News). This shrinking market results in a fierce battle for the same customers in order for companies to achieve growth targets. This competition has led to the need for manufacturers to price competitively based on the market and not product costs, which has resulted in smaller profit margins.

Customers

Another shift in the market is that customers are more knowledgeable and discerning. The Internet allows customers fingertip access to information critical to their decision-making. Vehicle specifications, model comparisons, safety performance, and on-line forums provide a wealth of information. Fifty-seven percent of automotive consumers used the Internet to research a vehicle purchase in 2002, while 17 percent of all new car decisions were influenced by Internet research (Source: Jupiter Research Corporation).

Automobile Complexity

Vehicle recalls are projected to be higher in the United States in 2004 than in any prior year. Figure 4 Provides a summary of recalls in the United States.

Analysts believe the record number of recalls stems in part from the increasing complexity of cars and trucks.

Figure 4. Automotive Recalls in the United States.

Year	# Recalls	# Vehicles
1993	221	8,408,950
1994	247	6,202,883
1995	265	18,121,565
1996	304	17,826,392
1997	265	14,712,658
1998	365	17,146,878
1999	396	19,376,291
2000	541	24,646,743
2001	454	13,626,263
2002	434	18,435,586
2003	528	19,098,101
2004 (as of Sept. 30)	462	14,353,883

Source: National Highway Traffic Safety Administration. Note the latest 2004 vehicle totals do not include recalls announced between early October and late November:

More Parts

Automobiles are complex products, typically consisting of more than four thousand parts. A number of market forces are driving the increase in product complexity. In the last two decades manufacturers have seen an increasing customer demand for features. High-priced options (e.g. automatic transmissions and power windows) are now standard equipment on most vehicles sold in the U.S. Even "Surprise and Delight" items such as backup warning sensors and remote keyless entry are now basic customer wants in many automotive segments. National and International safety standards are increasing in number and technical complexity (e.g. seatbelts vs. airbags). Fuel efficiency requirements are also driving complexity into automobiles, as designs must continue to be refined in order to reduce weight and frictional losses in order to improve efficiency. Environmental concerns including emissions and recyclablility are driving further complexity and change.

More Interdependencies

In addition to the increase in features and safety, emission, and fuel economy requirements, complexity has increased due to implementation of more sophisticated systems that interact in unique ways. An example is Volvo's Dynamic Stability and Traction Control (DSTC), which intervenes and corrects any tendency for the vehicle to skid. Sensors monitor the rotational speed of all four wheels, the driver's steering wheel input and the course of the car. A control unit processes critical signals. If a deviation from the norm such as the start of a rear-wheel skid is detected, the system activates the brakes as required to put the car back on course. The system also interacts with the Powertrain by reducing engine power if necessary. [4]

Human Limitations

The high level of product complexity has driven high levels of process complexity in the automotive industry. This high complexity drives an increase in complicatedness. Human cognitive ability limitations and human biases limit the individual's capacity to manage complexity and affect system design and performance. Probability biases, [5] limits of short-term memory, and limits on concentration and focus[6] drive the need for reducing product and process complexity. Studies have characterized the limits in human cognitive ability.

Miller's Law states that average human minds can deal with seven plus minus two things without the aid of external tools. [7]

Dynamic Complexity

Natural and human systems possess high dynamic complexity. The following highlights some of the features of systems that result in the rise of dynamic complexity as illustrated by Sterman[8], along with examples of how each can manifest in the auto industry. Dynamic complexity arises because systems are:

- *Dynamic*: Systems that appear to be constant are changing over time when considering an extended time horizon. An example of this in the auto industry is team composition on a vehicle program.
- *Tightly Coupled*: Elements of a system interact strongly with one-another and with the natural world. The vehicle package (where things go) introduces many dependencies as components vie for a particular piece of vehicle space.
- *Governed by Feedback*: Decisions alter the state of the world, causing changes in nature and triggering others to act, giving rise to a new situation, which then influences the next decision. This mechanism is apparent in the technical domain when considering the tuning of vehicle components (selection of suspension parameters) for vehicle dynamic attributes such as ride, handling and steering.
- *Non-linear*: Effect is rarely proportional to cause. Nonlinearity can arise due to basic physics, or as multiple factors interact in decision-making. This is apparent in the development of a vehicle for reduced noise, vibration and harshness (NVH). The sound at a passengers ear is the complex sum of

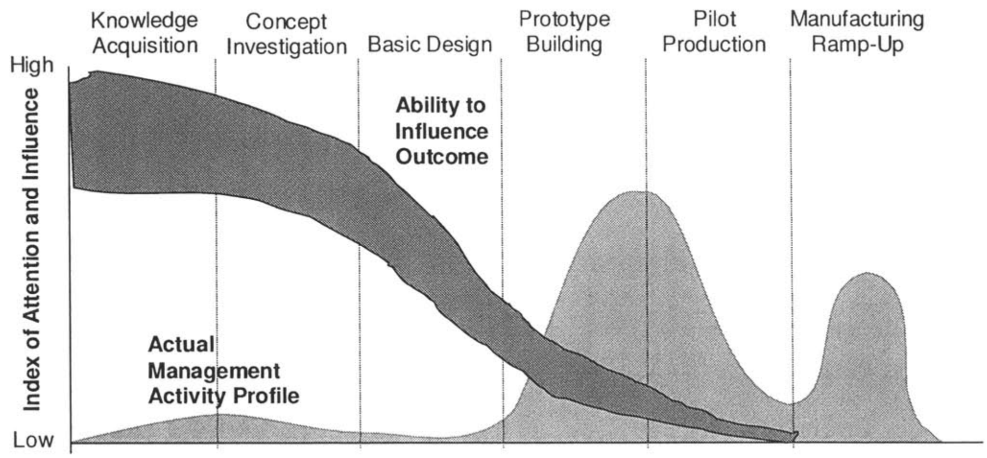
many vibration sources; reducing once source input does not have an equal effect on the overall sound level, due to the physical properties that govern the addition of sound sources.

- *History-Dependent*: Taking one action precludes taking others. Many actions are irreversible. This affect is apparent during the vehicle development process; once certain fundamental architectural decisions are made, there is no opportunity to change the path and maintain program timing.
- *Self-Organizing*: The dynamics of systems arise spontaneously from their internal structure. A small perturbation can be amplified and modified by the feedback structure, generating patterns in space and time and creating path dependence. An example of this in the auto industry is the addition of a "surprise and delight" feature into the automotive market. Customers' responses to the feature influence the competitive response and diffusion of the feature into the broader market.
- *Adaptive*: Capabilities and decision rules change over time in complex systems. Evolution leads to selection and proliferation of some things while others become extinct. Adaptation also occurs as people learn from experience. In product development at Ford Motor Company, there is an effort to transfer lessons-learned from one program to the next, which influences product and process design.
- *Counterintuitive*: Cause and effect are distant in time and space in complex systems, while at the same time there is a tendency to look for causes near the events sought to be explained. Attention is drawn to the symptoms of difficulty rather than the underlying cause. High leverage policies are not always obvious. This often manifests in the auto industry when considering the vehicle launch phase. At the launch phase of the program, the specific

problem is addressed effectively using standard problem-solving methods, but the root-cause of the existence of the problem is not addressed (e.g. lack of upfront knowledge and resources, lack of understanding of system interactions and emergent system properties).

- *Policy Resistant*: The complexity of systems overwhelms the ability to understand them. In many cases seemingly obvious solutions to problems fail or actually worsen a situation. The addition of new people to work on an issue with an existing team provides an example. In many cases the new people require training and information from the current team members, which can delay overall progress.
- *Characterized by Trade-offs*: Time delays in feedback in systems result in the condition where the long-run response of a system to an action is often different from its short-run response. High-leverage policies or actions can often cause worse-before-better behavior, while low-leverage policies often generate transitory improvement before the problem grows worse. This can manifest in the auto industry as it relates to cost-cutting: the immediate effects are positive (improved profit margins), while the potential long-term effects such as diminished product appeal can lead to lower sales and lower long-term profits. Blanchard and Fabrycky[9] illustrate the inconsistency between activity and ability to influence outcomes in Figure 5.

Figure 5. Management Activity vs. Ability to Influence Outcome, Blanchard and Fabrycky.



Appendix A provides an example of a simple system dynamics model for the Ford Taurus that highlights some of the dynamic complexity inherent in vehicle programs.

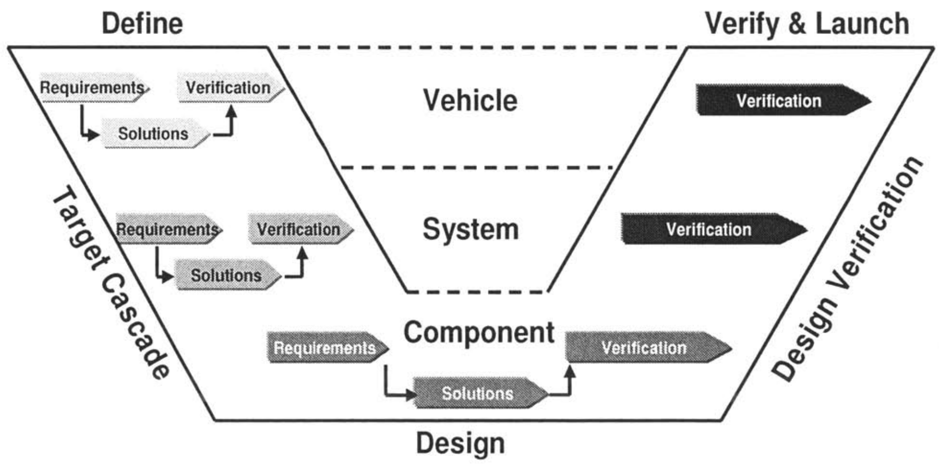
<u>Development Process at Ford Motor Company</u>

Product Development System

Ford Motor Company is transitioning from multiple regional vehicle development processes to one global process. The goal is to disseminate best practices among organizations and speed the development process. In the past Volvo, Jaguar, Mazda, and Ford in North America had separate processes. Ford's Product Development System (FPDS) is being refined and renamed as Global Product Development System (GPDS). While the transition of FPDS to GPDS is still underway, many of the fundamental building blocks of the processes are the same. Both processes are stage-gate and comprise of similar milestones. At the core of the Product Development Process is the "System

V", which is a model for the approach to manage the target setting, cascading or decomposition, integration or synthesis, and verification of engineering requirements. Figure 6 provides an illustration of the "System V." This process illustrates some of the major iterative loops in the design and development process at the vehicle, system, and component levels. This process emphasizes a top-down approach to the vehicle definition as manifested in targets and requirements.

Figure 6. Engineering System V Development Process.



Organization

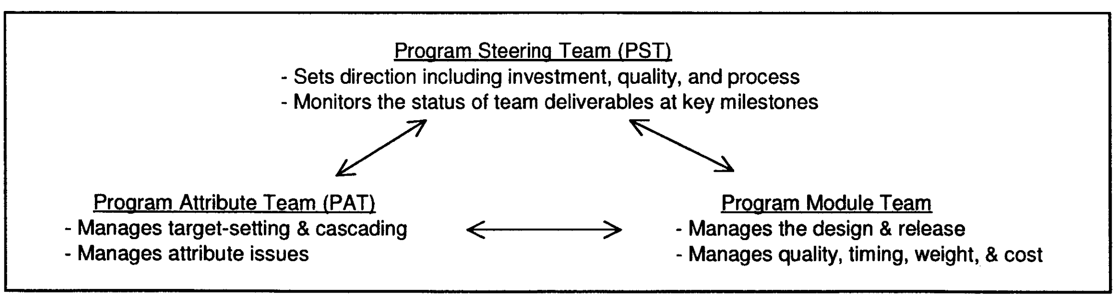
The increase in product and process complexity driven by the market has led to an increasing need to decompose complex systems into manageable pieces. This is accomplished at Ford Motor Company by partitioning the vehicle across product attribute and functional domains. Fifteen attributes define the product. Attributes include Safety, Vehicle Dynamics, Vehicle Package, and Noise/Vibration/Harshness (NVH). Figure 7 summarizes the attributes and functions.

Figure 7. Fifteen Attributes at Ford Motor Company.

Safety	Styling/Appearance
Security	Cost of Ownership
Package/Ergonomics	Thermal/Aerodynamics
Performance/Fuel Economy	Emissions
Vehicle Dynamics	Weight
Noise/Vibration/Harshness	Cost to the Company
Electrical/Electronic Features	Customer Lifecycle
Interior Climate Comfort Environment	

Program Attribute Teams (PAT's) are formed to facilitate communication for each attribute. Functional targets are set for the critical Attributes. Program Module Teams (PMT's) are formed to manage decisions for each of the key functional domains. The Program Steering Team (PST) manages the decisions affecting both the PAT's and PMT's. Figure 8 summarizes the general responsibilities of the teams.

Figure 8. Responsibilities of the Program Teams in Ford Motor Company.



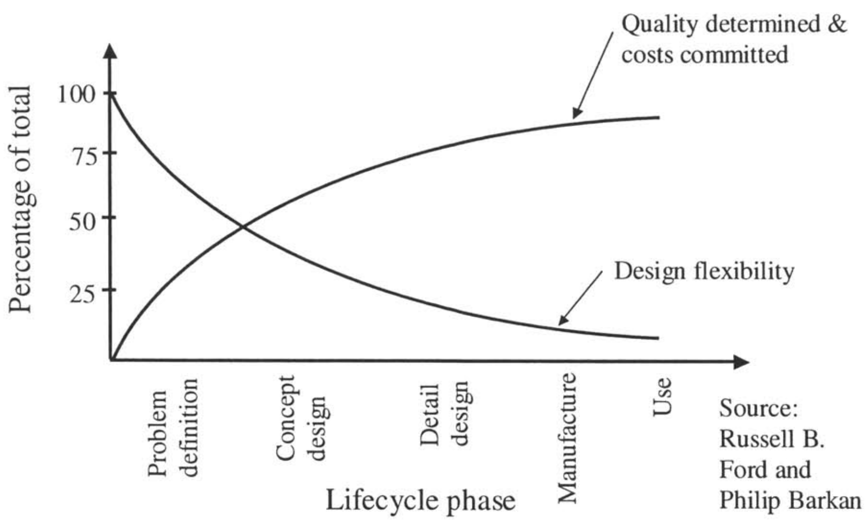
Noise/Vibration/Harshness and Vehicle Dynamics

The functional attributes of Noise/Vibration/Harshness (NVH) and Vehicle Dynamics are highly evolved at Ford Motor Company, as evidenced by the amount of internal training, the number of intranet web sites, and staff levels dedicated to each attribute. In both NVH and Vehicle Dynamics it is typical for engineers to stay in one functional area for most of their careers, due to the continually changing technical challenges and task variety that each attribute offers. This continuity is promoted by corporate initiatives such as Ford Motor Company's Technical Maturity Model (TMM), which is a staffing model designed to promote technical depth by aligning the reward and recognition systems and career advancement opportunities in a way to ensure that engineers stay in a specific discipline for up to ten years. While the NVH and vehicle dynamics attribute engineers typically stay in the same functional area, it is not unusual for movement within the attribute between vehicle programs and between sub-attributes such as Powertrain NVH and Road NVH.

Impact of Decisions

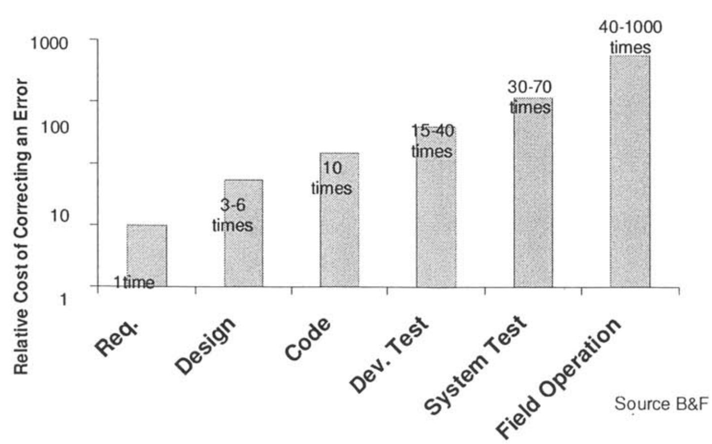
Successful accomplishment of engineering objectives requires input from a range of technical specialties along with a high level of expertise. Automobile development is a team activity, and it is important that individuals are aware of the important relationships between attributes. Decisions require consideration of interactions in the early stages of product development, when the majority of the quality, costs, and flexibility are determined. Figure 9 provides a simplified model of these relationships.

Figure 9. Quality, Costs, and Flexibility as a Function of Lifecycle Phase.



It is more difficult and costly to make changes in the later stages of vehicle development, due to the escalating financial commitments and accumulated output that requires rework. Figure 10 summarizes the typical relative cost of correcting an error in design.

Figure 10. Relative Cost of Correcting an Error as a Function of Time in the Development Process (Blanchard and Fabrycky).



Similar relationships exist in automobile development. These relationships drive the need to understand functional relationships at the earliest stages, where the impact of changes is minimized.

Approach to Decisions

Balanced Scorecard

Ford uses the Balanced Scorecard (see Figure 11) to "operationalize" the mission and strategy into a comprehensive set of performance measures that provides the framework for a strategic measurement and management system. This tool is intended to drive alignment and matching among different elements of the product creation process at the highest levels of the organization. The five priorities listed in Figure 3 are the main elements of the first column of the Balanced Scorecard, which includes Financial Health. The second column defines the "Back-to-Basic" (or Revitalization) priorities in Six Sigma terms. The third column reflects the key success drivers that directly impact the priority of f(x)s in 6 Sigma terms. The fourth column defines the Performance Measures for the priorities. Each of these measures has a corresponding target or metric, which is tracked by senior leadership. The table has been modified to maintain confidentiality.

Figure 11. The Balanced Scorecard.

Strategic Objectives	Balanced Scorecard Associated Metrics			
	Area of Focus	Priorities - F(x)	Success Drivers - Xi	Level I Performance Measures
1., 2. Improve Quality	Customer Satisfaction/Quality	Y_2: Fix Current Quality	Global / Enterprise wide Quality System Quality Leadership Initiative Continued Integration of 6-Sigma	3 MIS Vehicle Satisfaction 3 MIS TGW/1000 Six Sigma Waste Elimination ($ mils)
		Y_3: Sales and Service	Adherence to build and delivery schedules Vehicle operation/service experience Customer relationship management	Purchase/Sales Satisfaction Service Satisfaction Delivery Commitments -Deliver to Promise Week
3. Develop Exciting Products	Exciting Products	Y_5: Develop a Balanced/Competitive Product Plan	Cycle plan stability Better cycle planning tools Effective energy room	Number of changes in cycle plan Average age of portfolio vs. competition Capital Spending (mils)
3. Achieve Competitive Cost & Revenue	Financial Health	Y_1: Overall Financial Objectives	Align team around common financial metrics	Profit Before Tax (mils) Cash flow (mils)
	Customer Value/Costs	Y_8: Achieve Material	Full Cross Functional Ownership Proper resource allocation	Design material YOY cost reductions per unit Non-design material YOY cost reductions
5. Build Relationships	Relationships & People Development	Y_{10}: Build Relationships	Improve relationships with key constituents Commitment to diversity	Employee Engagement/Communication/Diversity Available Bench Strength for Key Positions

Tradeoffs

There are a number of challenges to the effective Management of tradeoffs among attributes within Ford Motor Company. Attribute engineers and supervisors report directly to their functional organization, with an indirect reporting relationship to the program Vehicle Engineering Manager. This promotes a shift in balance of decision-making with respect to priorities and resource allocation to the Functional Manager, who has a vested interest in delivering his or her attribute performance. With the high level of complexity, the Vehicle Engineering Manager has the challenging task to ensure that decisions are made to optimize and balance performance among attributes.

A Vehicle Integration (VI) function supports the Vehicle Engineering Manager by assessing the vehicle to targets. The task of managing tradeoffs and decisions between two attributes is difficult for this VI function, as the VI function does not have authority over each attribute. In addition a high level of knowledge of each attribute and attribute inter-relationships is required to make such tradeoff decisions. The VI function is left to monitor requirements and design verification and validation efforts, arrange program documentation and vehicle assessments at critical gateways, and plan and manage prototype vehicles.

A key decision support system that is utilized at the time of tradeoffs is the Product Attribute Leadership Strategy (PALS) document. The PALS document provides high-level positioning of key attributes in a vehicle segment context. For instance, a program strategy may be targeted for "Leadership" within a vehicle segment for vehicle dynamics and "Among the Leaders" for noise and vibration. This is the key document that attribute engineers use to set corresponding vehicle level subjective and objective targets.

A second challenge for Program Management and the Vehicle Engineering Manager is to make the best decisions between cost, weight, timing, quality, and function. While cost, weight, and timing can be quantified early in a program, the quality impact and functional or performance impact of decisions are more difficult to quantify. Low relative vehicle quality and functional performance can lead to lower customer satisfaction which can result in lower future sales. Cause and effect are distant in time, making it easier to attend to the near-term issues (e.g. cost and weight target deficiencies) rather than address the issues that manifest in the long run.

Summary

This chapter characterized the structure of the auto industry and highlighted key challenges that drive automotive complexity. A general description of the vehicle development process and organization at Ford Motor Company was then reviewed. Finally, the importance of decisions and a number of the tools used to support decision-making at Ford were discussed.

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Chapter 3. Literature Review: Automotive Suspensions, Attributes, Cascades, Design Structure Matrix, Axiomatic Design

Introduction

This chapter presents key concepts related to automotive design and development for the systems analyzed in later chapters and highlights literature influential in thesis development. First, automotive suspension function and terminology is discussed. Then a description of Vehicle Dynamics and NVH attributes is presented. Then the methods used to cascade attributes to design parameters are described. Finally, research papers related to the tools and case study under investigation are noted. A detailed description of the methods used in the thesis follows in Chapter 4.

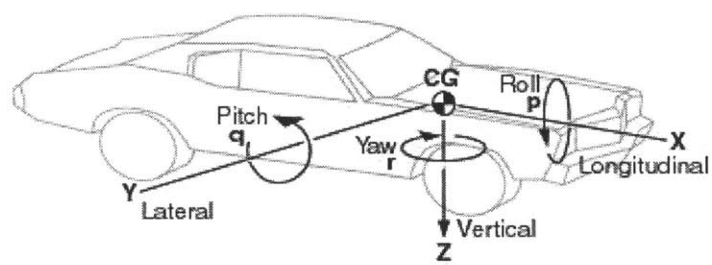
Automotive Suspensions[10]

The following describes automotive suspension function and terminology, providing background for non-automotive readers. Chassis bushing design parameters are then presented. Finally, two suspensions analyzed in a later chapter are then described. This information is relevant in the analysis of the technical challenge of rear suspension design as it affects vehicle dynamics and NVH, which is considered in more detail in Chapter 6.

Function and Terminology

The primary functions of an automotive suspension system are to provide vertical compliance to ensure that the wheels follow the uneven road to isolate the chassis, body, and passengers from the road, and to maintain the wheels in the proper steer and camber attitudes while reacting to control forces produced by the tires. Figure 12 shows the Society of Automotive Engineers (SAE) Vehicle Axis System.

Figure 12. Society of Automotive Engineers Vehicle Axis Definitions.



<u>Suspension Design</u>

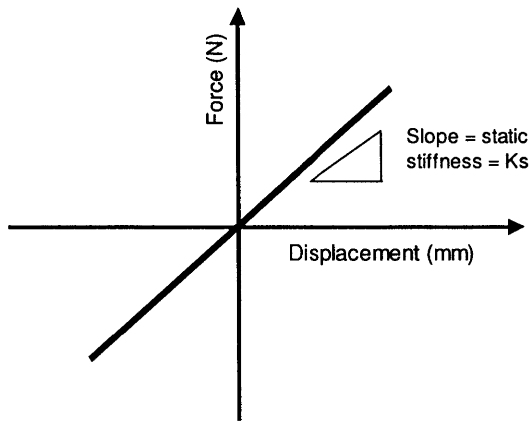
Vehicle Dynamics Compliance Strategy

In general, suspension geometry and compliance affect the transient handling of a vehicle. One of the goals of suspension design is to minimize the suspension geometry change during wheel impact to road perturbations and during braking. Typical design strategy for vehicle dynamics chassis design calls for an increase in suspension lateral stiffness to minimize deviation from specified kinematic function that leads to undesirable vehicle motion during impact, braking, and cornering loads.

Suspension Bushing Design

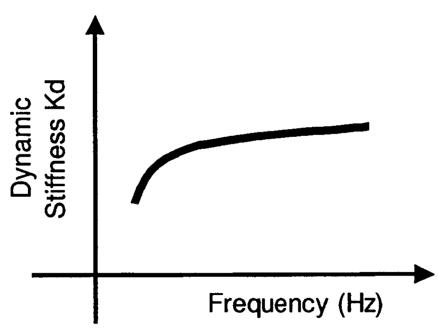
Bushings are the central components at the interface between NVH and vehicle dynamics. NVH engineers desire soft bushings that provide better isolation, while vehicle dynamics engineers typically desire stiffer bushings to reduce chassis compliance and to improve vehicle response and steering feel. For a chassis system, the bushing design requires optimization for NVH, vehicle dynamics, safety and durability. Vehicle dynamics desires bushings that meet static stiffness (K_s) requirements. Targets are set in terms of Load vs. Deflection curves as illustrated in Figure 13 below.

Figure 13. Static Load vs. Displacement Curve for a Suspension Bushing.



NVH engineers are concerned about the bushing isolation effectiveness at higher, audible and tactile frequencies. Requirements for bushings for NVH are defined as a dynamic rate, K_d, which is a function of frequency at a given force preload, as illustrated in figure 14.

Figure 14. Dynamic Stiffness vs. Frequency for a Typical Chassis Bushing.



A number of parameters affect the ratio of static to dynamic bushing rate. For a given design the following factors (ranked in order of importance) apply:

1) Compound Formulation - An elastomer specifically formulated for low damping properties is important, as it specifically targets minimizing Kd/Ks.

2) Rubber Volume/Durometer at Chosen Design Size - These parameters are coupled. Certain compounds offer improved flex life and offer maximum tuning flexibility. When compound type/durometer are selected and a primary rate target is identified, the rubber volume necessary to produce the part is identified.

3) Design Type - Mold-bonded and swaged bushings offer both excellent durability paired with favorable rate ratios. Some common rate modifiers are detailed below:

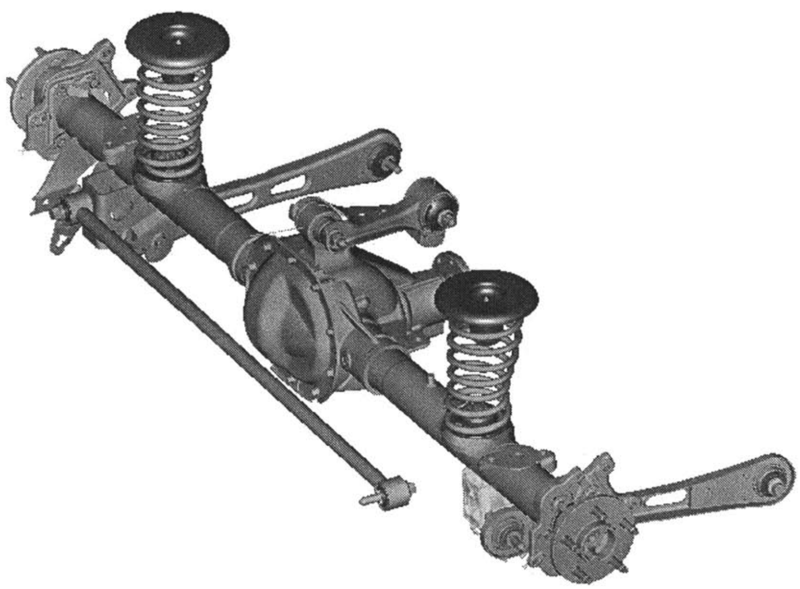
- Rate Plates - A rate plate's primary application is to allow for high radial rates with acceptable torsional angle capacities. K_d/K_s is typically comparable to a bushing without rate plates. The main effect occurs only in the shear rate(s) of the bushing.
- Voids - Voids serve to change the rate ratio(s) in a bushing. They can also change the response of a bushing to a specific load application (e.g. - a sharp turn up in rate after X mm of travel). A void placed in a primary load direction can offer soft vehicle on-center rates paired with more robust durability than an extremely soft solid bushing.

For a given static stiffness, an outside diameter increase will increase compound stiffness, having a net negative effect on decreasing the ratio of K_d/K_s. If matched with a corresponding inner sleeve ID increase, the Kd/Ks may increase only slightly, but the mass of the bushing and its load carrying capacity may trend toward over-designed.

Three-Link Solid Axle Suspension

Solid axles are designed such that the wheels are mounted at both ends of a rigid beam, so that movement at one wheel is transmitted to the opposite wheel, causing them to move together. Figure 15 below shows a typical three link solid axle.

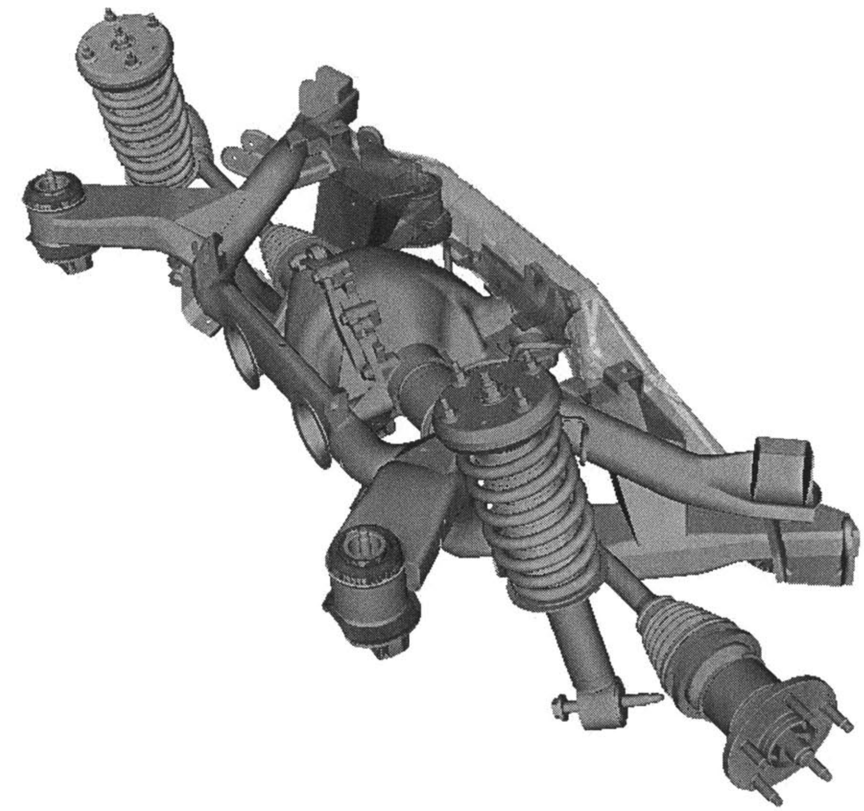
Figure 15. Three-Link (Solid Axle) Suspension.



Independent Short-long Arm (SLA) Suspension

Independent suspensions allow each wheel to move vertically without affecting the opposite wheel. Figure 16 shows a typical independent rear suspension.

Figure 16. Independent Rear Suspension.



<u>NVH and Vehicle Dynamics Attributes</u>

This section provides a more detailed description of the NVH and Vehicle Dynamics attributes, along with attribute cascades relevant to the analyses presented in future chapters.

NVH Attribute

The high-level attributes that define automotive NVH are listed in figure 17. There is a corresponding subjective and objective requirement or set of requirements for each attribute. Engineers in the NVH organizations are assigned to a specific program team. Within each program team engineers are assigned to work on one or more NVH attributes throughout the program development process.

Figure 17. Noise/Vibration/Harshness (NVH) Attributes.

Powertrain NVH	Road, Wind, and Squeak & Rattle NVH
Idle NVH	Coarse Road NVH
Acceleration NVH	Rough Road NVH
Deceleration NVH	Impact (Over Obstacles) NVH
Cruise – Smooth Road NVH	Smooth Road - Wind Noise
Automatic Shift NVH	Squeak & Rattle
Tip-in/Tip-out NVH	Vehicle Interior Noise Isolation
Take-off/Driveaway NVH	
Engine Start-Up/Shut-Off NVH	
Smooth Road (Medium Speed) NVH	

Electrical/Mechanical and Sound Quality NVH
Interior / Exterior Closures Sound Quality & Vibration
Interior / Exterior Electromechanical Adjustment Devices Sound Quality & Vibration
Primary Control Mechanisms and System Operation Sound Quality & Vibration
Secondary Control Mechanisms & System Operation Sound Quality & Vibration- Sound

NVH Cascade of Functional Requirements to Design Parameters

A cascading process is used to ensure that the necessary parameters are incorporated in the design to achieve vehicle level targets. Cascades also enable different areas to work separately on major systems such as the body, powertrain and suspension and provide a basis for cross-attribute trade-offs. Cascades are also used to show technical capability and identify performance gaps and organizational ownership.

Noise and Vibration engineers cascade vehicle level targets to subsystems and components utilizing a number of tools and processes. First subjective targets are cascaded to objective targets for critical attributes. Figure 18 provides a sample cascade for Road NVH.

Figure 18. Cascade Diagram for Road NVH From Subjective Targets to Objective Targets.

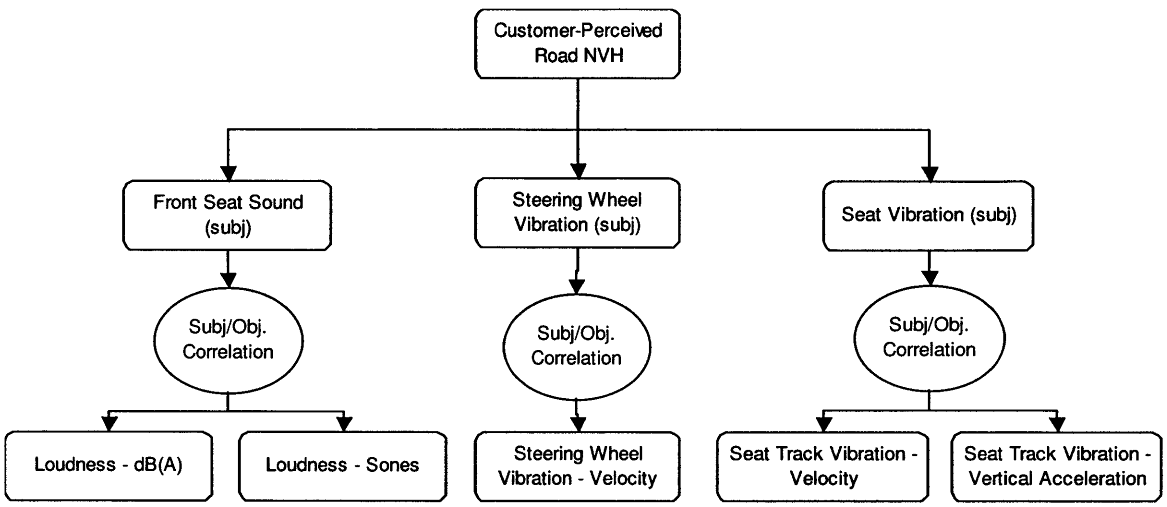
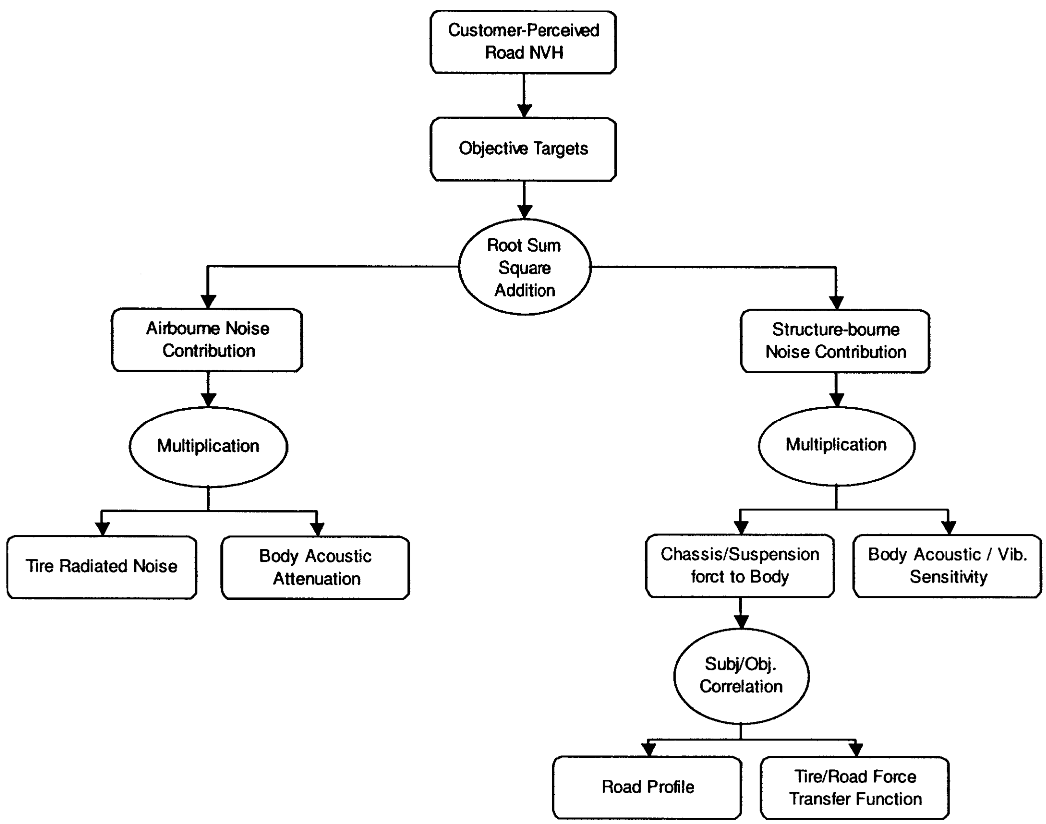


Figure 19 provides further cascading from objective system-level performance to subsystem and component performance in terms of design parameters. At this level, design engineers utilize a number of analytical and experimental tools to develop optimal designs considering functional performance, cost, and weight.

Figure 19. Processes and Methods to Translate Road NVH Attributes to Design Parameters.



This section demonstrated how NVH attributes are cascaded from functional attributes to actionable design parameters for the example of Road NVH. Similar cascades exist for the balance of NVH attributes.

Vehicle Dynamics Attribute

The high-level attributes that define Vehicle Dynamics are listed in Figure 20. Much like NVH, there is a corresponding subjective or objective requirement or set of requirements for each attribute. Engineers in the Vehicle Dynamics organizations are assigned to a specific program team. Within each program team engineers are assigned to work on one or more vehicle dynamic attributes throughout the program development process.

Figure 20. Vehicle Dynamic Attributes.

Ride
Primary Ride - Small & Large Amplitude Inputs
Primary Ride Control
Primary Ride Comfort
Secondary Ride - Flat & Rough Roads
Impacts - Small, Moderate & Large Inputs

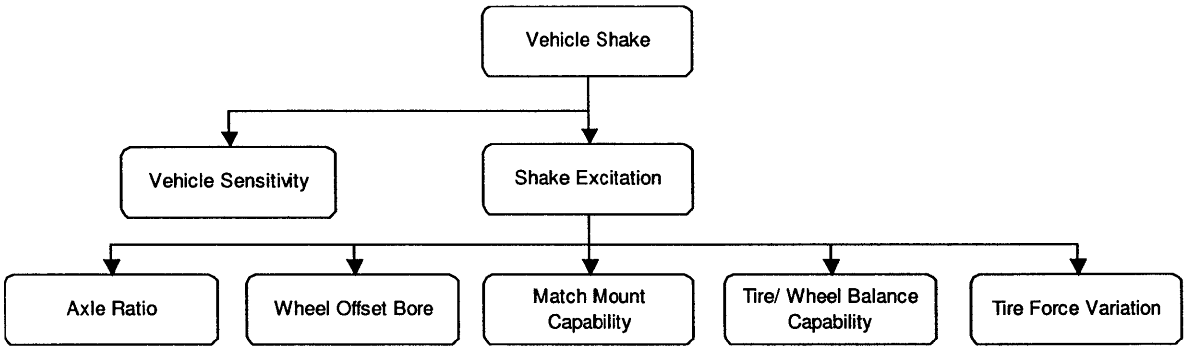
Handling
Cornering Stability
Transitional Stability
Straight Ahead Stability

Steering
Parking/Maneuvering
Straight Ahead Controllability
Cornering Controllability
Steering Disturb/Error States

Vehicle Dynamics Cascade of Functional Requirements to Design Parameters

The methods that vehicle dynamics engineers utilize to translate functional attribute performance to design parameters include computer simulation and on-road vehicle experimentation. The on-road vehicle experimentation will be considered in greater detail in a later chapter when the vehicle dynamics tuning process is analyzed. The vehicle dynamics engineer ensures attribute performance is met through proper selection of chassis systems and components. Potential vehicle error states that may be perceived by the customer due to component and build variation are also considered in the development process. Ride and Handling Health Charts are used to cascade attribute requirements to design parameters. The health chart mission is to deliver a set of requirements that provide fewer warranty and customer complaints relating to Ride and Handling. Figure 21 provides an example of a cascade for the vehicle dynamics sub-attribute of vehicle shake.

Figure 21. Processes and Methods to Translate Shake Attributes to Design Parameters.



This section demonstrated how vehicle dynamic attributes are cascaded from functional attributes to actionable design parameters for vehicle shake. Similar cascades exist for other vehicle dynamics attributes.

Related Research

This section notes some of the related works utilized directly or indirectly during development of this thesis. The works are organized by the method used. Note endnotes are used to reference sources throughout the thesis.

Design Structure Matrix (DSM)

1. Rinkevich and Samson[11] utilize the DSM to analyze the automotive powertrain attributes development process. In their research they determined that a significant percentage of interactions were not being modeled. Surveys of users indicated that, while the DSM was an excellent tool for capturing interactions, engineers were looking for more information such as the probability that an interaction exists, direction

and level of interaction, and simple methods for understanding the interactions.

2. Dong (formerly Hommes) and Whitney[12] present a technique to obtain a DSM from a design matrix, in an attempt to enable the use of DSM as an analysis tool early in the design process, when critical design decisions are made.
3. Dong[13] contributes tips to the process for developing a DSM to augment the methods and approach described in Chapter 4 and based on the work of S. Eppinger.
4. Yassine, Whitney, Lavine, and Zambito[14] suggest that the greatest benefit of a DSM model may come from "rewiring" or redefining relationships among elements and/or inserting new elements, instead of the traditional re-sequencing and partitioning tasks.
5. Daleiden investigates automotive flexibility as it relates to chassis design and organizational complexity and introduces heuristics for evaluating flexibility potential.[15]

Axiomatic Design and Suspensions

1. Suh and Deo presented an axiomatic design solution to remove the coupling in the steering and suspension systems by making the wheel alignment parameters independent of suspension travel.[16]
2. Guo and Xu[17] analyze suspension design using axiomatic design principles considering the suspension lift and collapse.

Summary

This chapter provided a discussion of key concepts related to automotive design and development for the systems analyzed in greater detail in later chapters. The next chapter provides a detailed description of the methods used in subsequent chapters.

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Chapter 4. Approach and Methods: The Design Structure Matrix and Axiomatic Design

Approach

The approach for the thesis is multifaceted and includes a case study, analysis of three levels of Design Structure Matrices and an Axiomatic Design Analysis. This chapter describes the methodology for each of these methods.

Case Study

The method of information gathering in the development of the thesis included informal interviews with a number of stakeholders involved in the design and development of a rear suspension system. The case study of a rear suspension system was selected as it met a number of the challenges inherent in large-scale systems. The case study provides the elements of a technical challenge and the integration of business and engineering issues, while encompassing detailed and broad issues that across different parts of the organization. Three engineers, three Supervisors, and three Managers were interviewed for this phase of the study. A discussion of the case study is included in chapters 5 and 6.

Design Structure Matrix[18]

Description

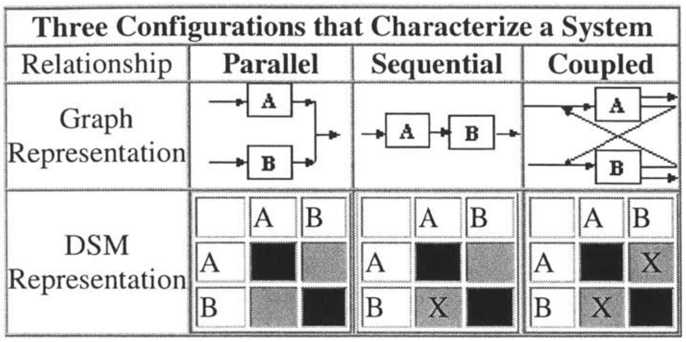
The Design Structure Matrix (DSM) can be used as a system analysis and project management tool. The DSM is a matrix representation of a complex system that identifies interactions between system elements. The Matrix contains a list of all of the relevant subsystems/activities and their dependencies. The DSM can provide insights into how to manage a complex system or project. The DSM highlights information needs and requirements, task sequencing, and iterations. Relationships are tabulated in a matrix format. Relationships under the diagonal represent the forward flow of information, while dependencies above the diagonal represent feedback flow. Figure 22 shows a sample Design Structure Matrix.

Figure 22. Sample Activity-Based Design Structure Matrix (Source: Ulrich and Eppinger, 1999).

ACTIVITIES		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Receive specification	A	A													
generate/select Concept	B	X	B												
Design beta cartridges	C	X	X	C											
Produce beta cartridges	D			X	D										
Develop testing program	E	X	X	X		E									
Test beta cartridges	F			X	X	X	F								
Design prod'n cartridge	G	X	X	X			X	G	X	X					
Design mold	H	X	X				X	X	H	X					
Design assembly tooling	I							X	X	I					
Purchase MFG equipment	J					X		X		X	J				
Fabricate molds	K								X			K			
Debug molds	L							X	X			X	L		
Certify cartridge	M					X						X		M	
Initial production run	N										X		X	X	N

Relationships in the DSM can be characterized in three ways: parallel, sequential, and coupled. Figure 23 summarizes the graphical and DSM representations for these characterizations.

Figure 23. Configurations That Characterize Design Structure Matrix Relationships.



Design Structure Matrix Uses

DSM's are useful for a number of representations and applications. Figure 24 summarizes some of the alternative uses for the DSM.

Figure 24. Alternative Uses for the Design Structure Matrix.

DSM Data Types	**Representation**	**Application**	**Analysis Method**
Component-based	Multi-component relationships	System architecting, engineering and design	Clustering
Team-based	Multi-team interface characteristics	Organizational design, interface management, team integration	Clustering
Activity-based	Activity input/output relationships	Project scheduling, activity sequencing, cycle time reduction	Sequencing & Partitioning
Parameter-based	parameter decision points and necessary precedents	Low level activity sequencing and process construction	Sequencing & Partitioning

Design Structure Matrix Construction

DSM construction involves a literature search/review of design guidelines and engineering requirements to determine candidate list of elements, interviews with content/knowledge experts to refine element list and determine interactions among elements, and representation of the resulting relationships in a matrix format. Once the DSM is constructed, the results can be reviewed and manipulated in order to improve the process. This reordering can result in fewer and/or shorter iterative loops, reducing the potential for rework and project delays. Among the tools of manipulation are partitioning, which is the reordering of rows and columns to eliminate or reduce the number of feedback relationships above the diagonal. For complex systems, the objective is to move feedbacks as close to the diagonal as possible, to minimize the number of elements involved in the iteration cycle. Tearing is the process of choosing the feedbacks that, if removed, will convert the matrix to a lower triangular matrix. Tearing reduces the set of assumptions that are needed to start the design process when coupled tasks are encountered. Banding is the identification of rows that constitute the critical path of the system or project. When two paths (rows) do not depend on each other, they can be banded and executed concurrently. Eppinger, Whitney, and Yassine provide additional insights into the DSM uses and advanced methods of analysis and simulation using the DSM.

Axiomatic Design[19]

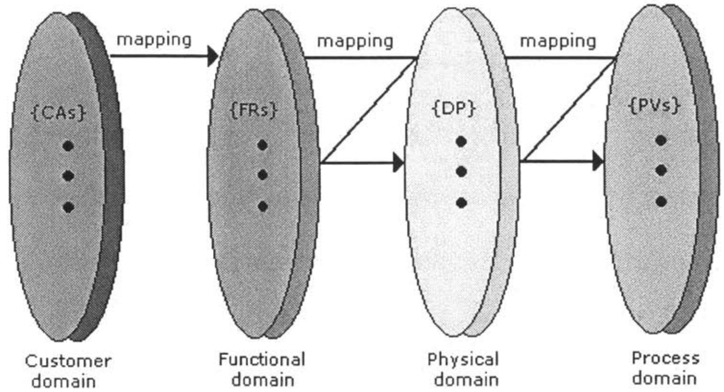
Design typically follows the process of understanding customer needs, defining the problem that must be solved, selecting a solution from possible alternatives, analyzing and optimizing the selected solution, and verification and validation of the resulting design. Axiomatic design is intended to reduce product development risk, reduce cost, and speed time to market by:

- Formalizing the design process
- Communicating the design to stakeholders at earliest possible time

- Improving quality of the design by analyzing and optimizing architecture
- Documenting and communicating the logical "how and why" of the design, not just "what"
- Identifying design issues early to reduce rework and design-build-test-redesign cycles
- Provide management with the dependency structure of the design, facilitating scheduling and organizational alignment.

Axiomatic design is a structured, evaluative method of design created to improve design activities by establishing criteria for which potential designs may be evaluated and by developing tools for implementing these criteria. Concepts of the Axiomatic Design process include the identification of domains, establishment of hierarchies within the domains, and "zigzagging" between domains to iterate on the design concepts while adhering to design axioms. Axiomatic design considers the existence of four domains in the design world: customer, functional, physical, and process. Customer attributes {CA's}, functional requirements {FR's}, design parameters {DP's} an process variables {PV's} are the characteristic vectors in each of these domains. Figure 25 summarizes these domains and vectors.

Figure 25. Axiomatic Design Domains.



The process is based on the decomposition of a system into Functional Requirements (FRs) and the introduction of appropriate system design parameters that provide the physical solution selected to satisfy the functional requirements. The Design Matrix (DM) is used to note the relationship between design parameters and functional requirements as follows:

$$\begin{Bmatrix} FR1 \\ \hline FR2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ A_{12} & A_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ \hline DP2 \end{Bmatrix}$$

Where A_{11} denotes the effect of DP1 on FR1, A_{21} denotes the effect of DP1 on FR2, etc.

The choice of design parameters and ultimately the physical embodiment of the design are guided by two design axioms:

- Axiom 1: Independence Axiom. Maintain the independence of all functional requirements.

- Axiom 2: Information Axiom: Minimize the information content of the design.

These axioms provide a basis for judging whether or not a design is "good." Each FR at each level of decomposition should have a corresponding DP intended to satisfy that FR.

Independence Axiom

Designs that do not satisfy the Independence Axiom are called coupled. Designs that satisfy the independence axiom are uncoupled or decoupled. The design parameters are totally independent for uncoupled designs. Decoupled designs have the situation where at least one Design parameter affects two or more functional requirements. The matrices in figure 26 summarize the relationships for the uncoupled, decoupled, and coupled designs.

Figure 26. Matrix Representations for the Uncoupled, Decoupled, and Coupled Designs.

	DP1	DP2	DP3	DP4
FR1	X	0	0	0
FR2	0	X	0	0
FR3	0	0	X	0
FR4	0	0	0	X

Uncoupled Design (preferred)

	DP1	DP2	DP3	DP4
FR1	X	0	0	0
FR2	X	X	0	0
FR3	X	X	X	0
FR4	X	X	0	X

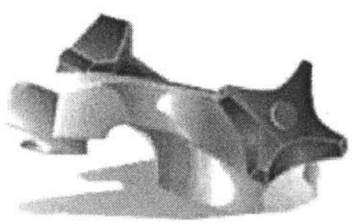
Decoupled Design (good)

	DP1	DP2	DP3	DP4
FR1	X	0	X	X
FR2	X	X	0	0
FR3	X	X	X	X
FR4	X	X	0	X

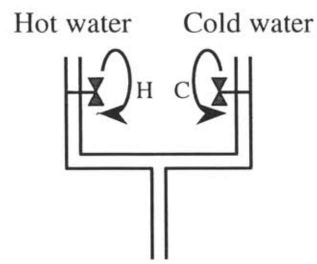
Coupled Design (Undesirable)

N. Suh provides an everyday example of the Independence Axiom as illustrated when considering water faucet designs. The two functional requirements for the faucet are to control the temperature and control the flow rate. In the first design, Figure 27, the two design parameters are the hot and cold water handles. This design is coupled because a design parameter (hot or cold handle) cannot be adjusted without affecting both design functions (temperature and flow).

Figure 27. Independence Axiom & The Coupled Water Faucet Design.

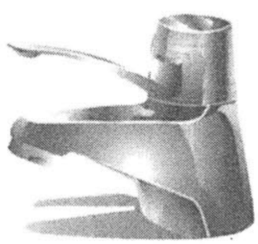


	DP1 Hot Valve	DP2 Cold Valve
FR1 Adjust Flow	X	X
FR2 Adjust Temp	X	X

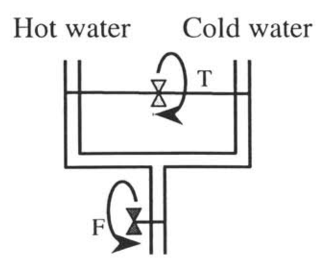


The faucet in figure 28 provides an example of a design that satisfies the Independence Axiom. The two design parameters, up/down and left/right motion are totally independent from the design functions. This design is said to be uncoupled.

Figure 28. Independence Axiom and The Uncoupled Faucet Design.



	DP1 Up-Down	DP2 Side-side
FR1 Adjust Flow	X	0
FR2 Adjust Temp	0	X



Information Axiom

The Information Axiom promotes the concept that when two or more alternative designs satisfy the Independence Axiom, the best design is the one with the least information. The "information" in this case is a measure of the freedom of choice and uncertainty. A mathematical construct for the Information Axiom is as follows: The probability of fulfilling a FR by a design alternative is p_i. According to probability calculus, the probability that all of the FRs are satisfied at the same time is

$$p_1 * p_2 * \ldots\ldots * p_n \qquad 0 < p_i < 1, i = 1, \ldots\ldots, n$$

Maximizing the probability that a design function is fulfilled is accomplished by minimizing

$$\Sigma \log_2 (1/p_i)$$

The logarithmic function is used because the information content requirements will be additive when there are many functional requirements that must be satisfied at the same time.

<u>Summary</u>

This chapter reviewed two systems engineering tools utilized in future chapters: the Design Structure Matrix (DSM) and Axiomatic Design Concepts. The Design Structure Matrix can be used as a system analysis and project management tool, while Axiomatic Design is a structured, evaluative approach to design. The next two chapters will apply these two tools to the automotive development and design processes.

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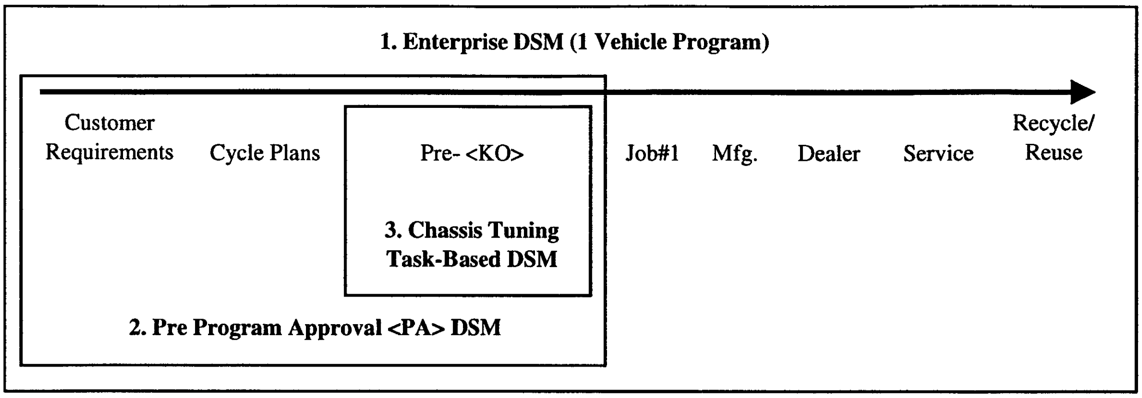
Design Structure Matrices

A key step in the development of the Design Structure Matrix (DSM) is the selection of the proper scope. Eppinger, Whitney, and Yassine [20] state that selection of too high a level of system abstraction might oversimplify the design process and tend to ignore important sub-system interactions, while selection of a system abstraction at a lower level may lead to diminished intuitiveness of the DSM as the identification of important sub-system interfaces becomes more difficult. They suggest that these difficulties can be overcome by building a hierarchy of DSMs at different levels of abstraction. The idea is to cascade the DSMs to increasing levels of detail until such time as certain desired interactions are apparent at the lowest level. This chapter provides a summary of a series of three Design Structure Matrices (DSMs) that provide insights from three levels of abstraction. The first DSM was completed by a team of students including the author as part of the Integrating the Lean Enterprise Course at MIT. [21] The second DSM was developed by a team as part of the course in System Design and Management at MIT.[22] The author generated the third DSM after review of process and design guideline documentation and consultation with engineers involved in chassis system development at Ford Motor Company. The three DSMs and three levels of abstraction are summarized as follows:

1. An activity-based DSM across the Enterprise for a vehicle program.
2. An activity-based DSM within a vehicle program prior to program approval.
3. A task-based DSM for a vehicle chassis tuning effort.

Figure 29 provides a graphical representation of the DSMs.

Figure 29. Design Structure Matrices: Three Levels of Abstraction.



Enterprise Design Structure Matrix (DSM)

This section describes the method, results, and insights gained from the analysis of the enterprise using the Design Structure Matrix.

Method: Enterprise DSM

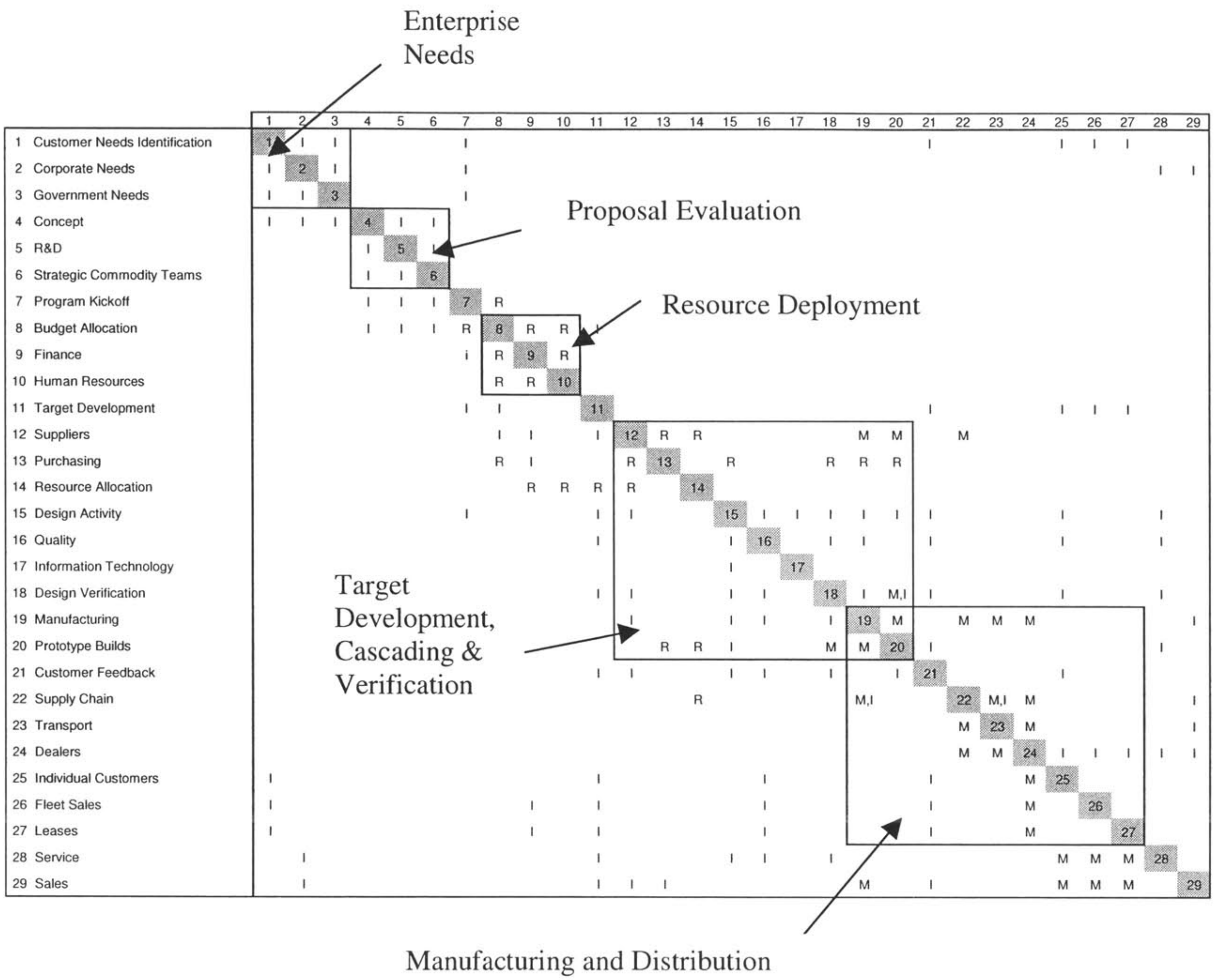
The first DSM was developed for a vehicle program across the automotive enterprise. The team developed the Enterprise DSM after completing the process of Enterprise Value Stream Mapping. The Enterprise Value Stream Mapping and Analysis (EVSMA) comprised of eight steps:

1. EVSMA Kickoff: Provides motivation, roles & responsibilities, and training.
2. Stakeholder Value Exchange: Identifies stakeholders and their contributions to the enterprise, along with the relative importance.
3. Strategic Objectives: Identifies the strategic objectives of the organization.
4. Enterprise Processes: Defines the boundaries and processes being analyzed.

5. Enterprise Interaction: Assesses flow by investigating interactions among processes & stakeholders.
6. Enterprise Waste: This section identifies the enterprise level waste in the current state in terms of production, information, and enterprise waste. Examples include waiting, transportation, inventory, processing, rework, and defects.
7. Future State: This step creates the vision or desired state for the Lean Enterprise.
8. Improvement Plan: This outlines the steps required to close the gap between the current and desired states.

The scope of the Enterprise DSM includes relationships beyond the Product Development Process. The relationships among the 29 tasks identified are shown in Figure 30. Significant interactions were represented in the DSM by type of interaction with "i" representing information exchange, "m" representing material movement and "r" representing resource flow, which includes money and people flow.

Figure 30. Enterprise Design Structure Matrix.



Findings: Enterprise DSM

The team identified five task groupings or interaction blocks, named in this analysis as follows:

1. Enterprise Needs.
2. Proposal Evaluation.
3. Resource Deployment.
4. Target Development, Cascading & Verification.

5. Manufacturing and Distribution.

The following describes each iterative block along with insights gained from review of the high-level system analysis.

Enterprise Needs Block

The first set of coupled tasks encompasses key needs of the enterprise. Customer, corporate and regulatory needs are considered during multiple iterations by planning and marketing. This process typically takes six months to converge on a proposal for a new or freshened vehicle. This block is vulnerable to rework due to changes in market conditions, corporate financial state changes such as cash flow constraints, and government legislation actions.

Proposal Evaluation Block

The second process block is comprised of steps to evaluate the potential of successfully meeting the Enterprise Needs criteria. The team identified a number of considerations that are addressed in this phase of the program:

- Is the technology proposed "Implementation Ready" (IR) or will it be IR by the target development stage?
- Can the proposal meet safety and emission requirements?
- Will the concept meet high-level vehicle packaging and quality requirements?
- Can the requirements meet the platform, system and component strategies for commonality and reuse developed by the Strategic Commodity Teams?

This assessment takes approximately six months. A Pre-Program team summarizes the assessment, including the financial analysis. The data and recommendations are reviewed in a series of meetings to achieve approval for program kick-off <KO>. If <KO> is not granted, the process is re-started at the Enterprise Needs Block. At this stage of the process major funds are not committed and minimal engineering resources are used. The most critical aspect of this block is the effective alignment of product assumptions with anticipated market needs. There are a number of examples in the auto industry of products that meet regulatory and quality requirements but do not interest the customer. The result is lower-than-projected sales volumes, reduced profits, and unacceptable returns on investment. One of the more difficult tasks is to project accurate sales volumes. There must be discipline to resist the temptation to inflate sales projections in order to improve financial projections. Sales volume over-projections can lead to excess capacity and the commitment of scarce resources to efforts that do not contribute to corporate profits.

There are a number of mechanisms built into the process to promote a disciplined adherence to program gateway deliverables. The first is the establishment and explicit identification of inviolable deliverables at each gateway. Inviolable deliverables are deliverables that can not be traded off or compromised. Written quantification of completion of inviolable deliverables must exist. The second mechanism to promote adherence to program disciplines at major gateways is less explicit and amounts to consensus building. Senior management seeks commitments from major constituencies and stakeholders with respect to their ability to deliver to the program objectives. A high level of career risk and reward is placed on the Program management at this time. History has shown that when chief program engineers do not deliver a product that meets performance requirements for critical metrics careers are adversely affected. On the other hand, if the team delivers to the program objectives the chief program engineer typically is rewarded with promotional opportunities.

Resource Deployment Block

Once a program is approved, the third coupled group of tasks initiates resource deployment. Decision support systems are used to establish the engineering and prototype resource budgets and detailed financial assumptions at this stage. The first process uses the program information including the magnitude and scope of change to forecast engineering and prototype requirements. The second process involves the collection and analysis of detailed information in order to refine financial assumptions. Once agreed, the funding and engineers are deployed to work on the program. Issues with the staffing, prototypes, or cost projections are addressed in the plan before it is submitted for re-approval. This process block is subject to change and rework due to corporate initiatives external to the program. Organizational headcount reduction tasks and prototype cost reduction efforts that are prescribed to programs independent of program resource requirement needs analyses are examples of such externalities.

Target Development, Cascading & Verification Block

The next process block involves target development, cascading and verification. This cluster of tasks encompasses the Ford Product Development System (FPDS) process. A new program process can take up to 52 months to complete, depending on the program scale. Iteration occurs at this time due to the constant flow of new information, material and resources from design activities. Changes can occur as a result of prototype builds/drives, unanticipated test results and manufacturing readiness assessments. If issues are not resolved within the target development and cascading block, it is typical for the process to loop back to the resource deployment block. There is also the potential to loop as far back as the Enterprise Needs Block, where there is a risk of canceling the program.

Manufacturing and Distribution Block

The fifth major grouping of interactions takes place in the manufacturing and distribution stages, mainly by way of material and information flow. This group of tasks includes the program launch phase of the process. Communication and urgency levels increase as pre-production vehicles go through the assembly process. Changes are discouraged at this stage of the process. Decisions have to be made expediently in order to minimize the potential of delaying the start of production. Unintended interactions in the complex systems or unanticipated effects of component variation are discovered at this stage. Rework can result in costly delays in vehicle shipment and sale. Release of vehicles with suspect quality can result in high initial warranty costs and potential recalls.

Insights: Enterprise DSM

The Enterprise is shown to be a useful tool to highlight critical interactions and to facilitate dialog among constituencies. The DSM representation at the Enterprise level also provides a way to highlight risks and communicate lessons-learned through utilization of examples and case studies. While there can be debate about the strength and nature of the interactions highlighted in the Enterprise DSM due to over-simplification at the high level of abstraction, the analysis does yield useful insights. This section summarizes a number of the insights that emerge from analysis of the Enterprise DSM.

At the enterprise level, iterative loops are long. Long product development cycles increase the difficulty of aligning product attributes and customer wants and increase the level of rework due to changing customer needs (Task 1). Examples of the lack of alignment of customer wants and product assumptions are apparent throughout automotive history, with examples that include the Edsel in 1957 and the Pontiac Aztec in 2000. Both products did not meet the customer need for preferred styling, resulting in poor sales, which led to unmet corporate needs (profits). In circumstances where products do not satisfy customer wants, product updates must be incorporated sooner than originally planned. This can manifest in major styling and product "freshenings" in one or two years after product release, or in the ultimate cancellation of the product and elimination of use of the brand nameplate in the marketplace. This also generates significant waste, as the investment in brand equity is lost.

Government Needs (Task 3) can introduce another significant iterative loop in the Enterprise DSM. Major automotive systems such as the body structure must be designed upfront to meet Government safety regulations that may emerge throughout the platform lifecycle, which can be more than ten years. If future Government requirements are not anticipated upfront, the platform reuse and extension opportunities are limited.

Another example of the high level interactions involved at the enterprise level relates to purchasing and supplier selection (Tasks 12 and 13). Global monetary fluctuations can lead to adverse effects on the costs and financial performance of the program. Recognition of this interaction can lead to improvements in the sourcing strategy in order to improve robustness to variation in global monetary fluctuations and supplier business practices.

Design Verification (Task 18) presents interactions that, if not managed, can result in significant program rework and added costs. If the design does not meet performance requirements, redesign or changes to program assumptions is necessary. The impact of an unmet functional requirement can manifest in the deletion of a planned vehicle option in the event that the unmet requirement involves a non-critical subsystem or feature. Another impact of unmet requirements is late changes to the program, which increase the risk that quality issues will reach the customer.

The level of fleet and lease sales (Tasks 26 and 27) can have a financial impact on the vehicle program. Increased levels of fleet sales can lead to lower vehicle residual values. The residual value is the amount that a customer can purchase the vehicle for at the end of a lease. Lower residual values result in the need for the company to set higher monthly lease payments in order to meet sufficient overall profits on the lease transaction. High volumes of off-lease and fleet vehicles in the market lead to lower resale values. The resale value is one of the factors considered in vehicle purchase and is an influential element in consumer buying guide recommendations in such publications as Consumer

Reports. Appendix A provides a simple model of a number of the system dynamics of program decisions.

Conclusions: Enterprise DSM

The Enterprise that delivers an automobile is highly complex. Involved are many relationships and interactions among people handling the millions of tasks required to translate an idea into a tangible product in the marketplace. Success in the automotive industry can result only as automotive companies continue to acknowledge and develop the mechanisms, tools, processes, and people capable of embracing and managing this complexity. The relationships in the highly abstract, simplified Enterprise DSM presented can be debated. The Enterprise level DSM is not intended to be a prescriptive tool for the auto industry, but rather a descriptive tool to allow individuals with a wide range of experience and backgrounds the ability to communicate with one another.

Information Management

Information flows permeate every level of the organization, as exhibited in the Enterprise DSM. This highlights the need for and significance of a sound corporate strategy to facilitate information flow. Ford Motor Company has invested significantly in information systems at many levels and within many domains. A recent interoffice news profile of Dr. Richard Riff, the Ford Technical Fellow in computer-aided engineering includes a story about a very old-fashioned technologist -- the village cobbler of centuries ago highlights the challenge.

"The cobbler knew how much his customers could afford to pay and what kind of shoes they needed. He sketched the shoes, then made them and sold them. When a shoe was damaged, he fixed it. And when the villagers found their shoes wearing out, they brought them back to the cobbler, who reused the leather in new shoes. The cobbler had mastered every stage in his product's life cycle -- market research, design, manufacturing, pricing, sales, service and recycling. The flow of information was flawless because the phases of the life cycle were contained inside a single brain. The life cycle of a Ford automobile, Riff points out, contains precisely the same phases. But information about the phases is split into a million fragments and spread around the entire world, among countless brains and computers. The task ahead, Riff says, is to reconstitute the mind of the cobbler -- to bring all the information back together in a seamless system."[23]

Ford Motor Company's strategic information management approach is referred to as C3P, an acronym of acronyms that stands for computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), and Product Lifecycle Management (PLM). This strategic initiative is critical in the increasingly complex global automotive market.

Pre-Program Design Structure Matrix

The enterprise level Design Structure Matrix identified insights at the highest level, simplifying the interactions in order to gain a perspective of the overall automotive enterprise function. Insights from the Enterprise DSM highlighted the importance of making the proper decisions in the early program stages in order to minimize large iterative rework loops later in the product development and production process stages. In this section the focus is sharpened in order to understand the interactions involved in the critical pre-program process in more detail.

Method: Pre-Program Approval <PA> DSM

The objectives of the development and analysis of the DSM at the Pre-program level were to determine the critical iterative loops, key interfaces, and opportunities for process simplification through task re-sequencing and matrix partitioning. The approach involved the collection and review of FPDS process documentation, review of program-specific data (history) for two programs, and stakeholder interviews. The FPDS task list from program kick-off, <KO> to Program Approval, <PA> consisted of more than 800 items. These items are associated with the left side of the "V" on the "system V" model. The tasks were reviewed, filtered, and synthesized in order to reduce the number of tasks to a manageable level prior to DSM construction. Non-critical, low-level, and non-program functional tasks were removed and parallel, similar tasks were consolidated. Figure 31 outlines the Pre-program DSM task list development.

Figure 31. Pre-Program <PA> DSM Task List Development

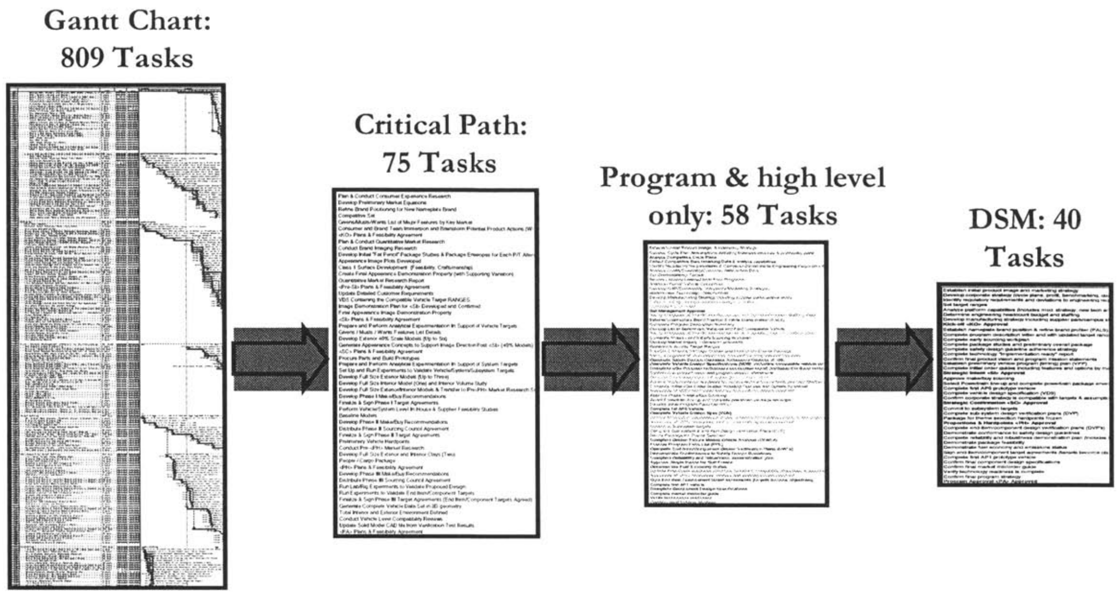
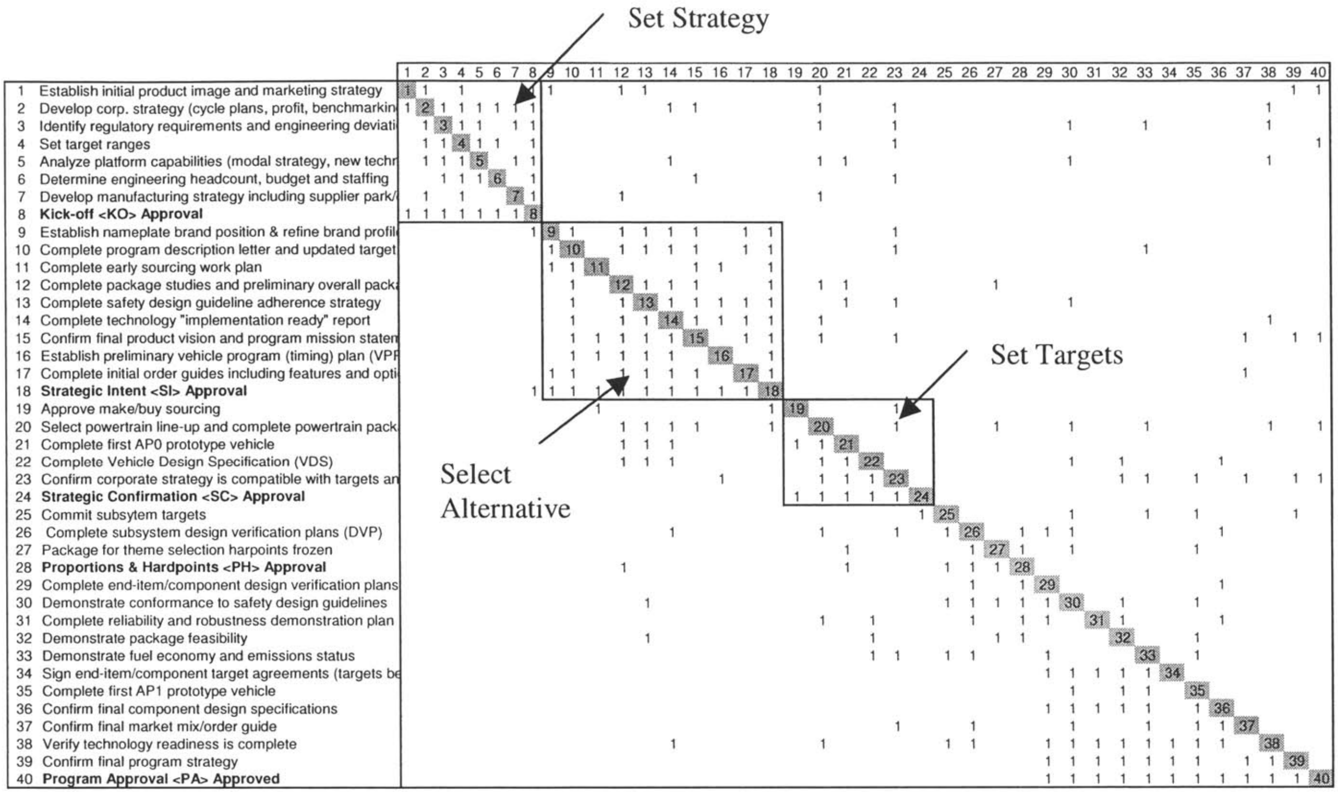


Figure 32 highlights the critical interactions identified in the analysis of the DSM. Note the detailed steps of the DSM are omitted to maintain confidentiality.

Figure 32. Pre-Program Approval Design Structure Matrix.



Findings: Pre-Program DSM

The Pre-Program DSM provided more detail in terms of task definition and interactions among the tasks than the Enterprise DSM. Three prominent iteration blocks emerge from the Pre-Program DSM. The team's task re-sequencing exercise resulted in only a few task sequence changes, which provided little impact to the overall process. The three iteration blocks are identified; the Set Strategy, Select Alternative, and Set Targets blocks. In general programs iterate within these blocks and do not return to earlier blocks, with a few exceptions. There have been cases where external market or internal financial conditions have driven change and iteration that skips back more than one block. Such iteration can introduce significant delays, rework, and risk to programs. The following sections describe the three blocks in more detail.

Set Strategy Block

The Set Strategy Block considers the product options given the financial and resource constraints along with the high-level market wants. At this stage information external to the program is a key driver in program assumption development. Some of the questions answered at this stage of the program include the following:

- Does the program fit within the limits and capabilities of the platform constraints?
- Is it generally feasible, including profitability, targets, resources, and strategy?
- Does manufacturing and supply chain capacity exist?
- Can it compete in the marketplace?

Select Alternative Block

The Select Alternative Block selects a prime alternative among alternatives and adds refinement to the plan and assumptions. During this iteration loop, the program proposal communicates assumptions to the functional areas in order to establish design feasibility confirmation. Iterations take place as tradeoffs are made. This group of tasks is critical in balancing the product between styling, safety/regulatory and attributes. Multiple iterations of this loop take place due to the resources and investment required to continue beyond this point in a program.

Set Targets Block

The Set Targets Block answers the question of "How do we do it?" The focus is on the cascade of requirements both from system to component level and downstream to production requirements. The information from the Target Development and Cascading Block is further developed in order to confirm the program strategy. Targets are cascaded at the later stages of this block from the vehicle and system levels to the subsystem and component levels. The potential cost and timing impact of requirement non-compliance can be significant post <PA> as iterative loops are large and may involve target deviations or program assumption changes. It is critical at this stage that functional targets are balanced with cost, weight, quality, and timing requirements. This stage in the process takes approximately one year. In many instances analytical verification methods are used to highlight and correct potential issues that can lead to requirement non-compliance. Component bench tests are another method used to decouple verification test plans in order to allow parallel work streams. Late rework discovery especially close to <PA> causes major timing issues. A typical response of rework discovery is to compress downstream activities in order to maintain vehicle production and Job<1> dates. A slip in Job<1> date can result in the loss of competitive advantage in the marketplace and a loss of confidence among Wall Street investment and credit rating analysts.

Key Interfaces

Criteria were developed to determine the key Interfaces in the Pre-Program DSM, including considerations such as the potential for major rework or retiming in the event that a particular requirement is not met. Based on the considerations identified, the team highlighted the following as key interfaces in the Pre- <PA> DSM:

- Marketing and Engineering: Must achieve market wants, must be functionally achievable.
- Engineering and Finance: Must be functionally achievable and affordable.
- Engineering and Manufacturing: Must meet function and must be able to assemble it.
- Marketing and Finance: Must be able to sell X amount and provide Y ROI.

Examples in the auto industry where key interfaces were not managed until late in the development process, when a high level of costs were incurred, include the following:

- Marketing and Engineering: Designing and developing a vehicle for an overseas market then determining not to ship the vehicle. Installing a low-powered engine in a vehicle then deciding not to sell it.
- Engineering and Finance: Designing and developing a vehicle with sophisticated systems then reverting to simpler, lower cost systems later to achieve profitability.
- Engineering and Manufacturing: Developing systems that cannot be assembled due to package constraints.

While these examples do not occur often, the costs of such situations can be significant due to the long iterative loops and substantial resources involved.

Insights: Pre Program Approval <PA> DSM

Opportunities to Simplify

The Pre <PA> process is complex. Efforts that lead to a reduction in the complicatedness provide high leverage and minimize the potential for mismanagement of interfaces that have a significant impact on the success of the program. The general insights follow.

1. Decouple generic information from program-specific information. Information decoupling will allow the removal of generic information requirements from the critical path, which will allow the team to focus on the program-specific information and communication. Generic information that is removed from the critical path can be maintained on an on-going basis so that the information is available when required by the programs. Examples of such information include market data, quality data, and objective performance data for the relevant competition.

2. Communicate downstream risks upstream to reduce the potential of rework. There is a great deal of information that can be reviewed to ensure that mistakes made on vehicle programs in the past are not repeated. Examples of such information include the analysis of late changes of past programs and the root-causes for the changes. Databases such as Global 8-D's and 6-Sigma DMAIC reports can be

reviewed to ensure that the issues that could affect the new program are considered upfront. Global 8D refers to an internal Ford Motor Company best practice problem solving process and computerized archival system that merged elements of different organizational approaches to solving problems into one process and one database. The corporate-wide process and supporting system is available to employees and suppliers in an effort to provide a common source of lessons learned. Six-Sigma is a methodology that applies a set of statistical tools to help improve quality in an organizations products and services. It attempts to systematically reduce variability in any business or manufacturing process, while also reducing or eliminating defects. The core of the Six Sigma methodology is referred to as DMAIC - Define, Measure, Analyze, Improve and Control.

Conclusions: Pre-Program DSM

Where the Enterprise DSM analysis emerged with the central conclusion that stressed the importance of a comprehensive information management strategy, the Pre-Program analysis stresses the importance of interface identification and management and reuse strategies.

Interface Management

Interface management is accomplished in a number of ways and in a number of domains at the Pre-Program phase of the automobile development process. The organizational structure can be aligned to facilitate communication between individuals. At Ford Motor Company, the organization has oscillated from a program-based to a functionally based emphasis. Organizational differences lead to differences in incentives and individual performance criteria. The scope of this thesis does not include the analysis of the strengths and weaknesses and particular recommendations for organization structure, but rather focuses on the need to establish explicit interfaces for critical requirements and where critical decisions are made. This will allow the team to function more effectively regardless of the type of organizational structure deployed. When interfaces are made explicit, e.g. through requirements management, people better understand their role in terms of information transactions. Dong[24] points out in DSM development that people are reasonably accurate in answering what "information" they need before they can do there job, and where to get this information, but are less aware when it comes to knowing where their information goes and who uses it. Strategies that foster interface management include co-location of teams and an explicit meeting cadence, which facilitate communication of expectations and deliverables.

Reuse

A number of program specific conclusions are apparent when one considers the Pre-Program DSM and the automobile company that produces multiple products. The first is that there are significant benefits of reduced rework and iteration through the reuse of platform, system, subsystem, and components. Thoughtful reuse of platforms, systems, subsystems, and components can reduce the level of resources required for many of the tasks highlighted in the Pre-Program DSM (figure 32). Many steps in the process are simplified through reuse. Many tasks become information-based instead of test or analysis-based when incorporating a reuse strategy. For example, verification for a particular functional requirement that is reused typically involves the confirmation of the validation information, rather than conducting additional component test and analyses. Reuse also allows the Enterprise the opportunity to manage the overall scope of the product and production portfolio and smooth resource allocation. A number of the automotive manufacturers will elect to change one major system such as the body, chassis, engine, or assembly plant at a time, so as to reduce complexity and minimize the potential for significant rework.

Vehicle Chassis Tuning Task-Based DSM

The enterprise and pre-program DSMs considered the interactions among activities on a vehicle program. Interactions that take place at a lower level of abstraction are considered next. The analysis that follows is an investigation of the task sequence for chassis tuning for vehicle dynamics and NVH. The goal is to highlight critical interfaces that affect both attributes and to extract insights relative to task sequence and the overall process. The scope of the DSM includes the chassis "tunable" parts. These consist of the suspension components that require modification once vehicle prototypes are available and overall system performance can be assessed.

Method: Task-Based Chassis Tuning DSM

A chassis tuning Design Structure Matrix was developed with inputs from tuning process documentation and Vehicle Dynamics subject matter experts. The original task list consisted of twenty-nine (29) tasks. The build, final assembly, pre-tuning, and tuning subtasks were consolidated from seventeen (17) to four to simplify the analysis.

Findings: Task-Based Chassis Tuning DSM

The chassis tuning DSM is summarized in Figure 33. If the desired vehicle dynamic properties do not meet target levels, one of two things occurs: either a target deviation is submitted or the process iterates back to the suspension geometry, necessitating significant rework. The chassis tuning process DSM indicates a process that is generally well sequenced, with no significant re-sequencing opportunities to reduce time or rework. This is the result of an evolved process that has been applied by an engineering community with a significant history with and knowledge of the tuning process.

The importance of ordering the proper range (stiffness, damping, etc.) of tuning component alternatives is apparent when considering the potential feedback steps. If the vehicle does not exhibit target performance levels while meeting functional requirements once the tuning process is complete, additional parts may be necessary. This will result in long delays as parts are ordered, fabricated, and measured. A second insight from review of the task-based DSM is the high level of iteration involved in the tire, bushing, and shock tuning block.

Figure 33. Task-Based Chassis Tuning Design Structure Matrix.

	Order Tuning Parts	Build Checks	Final Assy Checks	Pre-tuning Checks	Tuning Checks	Select Springs	Select Anti-roll bars	Select Dampers and damper mounts	Select Tires	Select Bushings and body/frame mounts	Set Suspension and steering kinematics	Set Steering friction & boost, suspension alignment
Order Tuning Parts	1					X	X	X	X	X	X	X
Build Checks		2	x									
Final Assy Checks		X	3									
Pre-tuning Checks				4								
Tuning Checks				X	5							
Select Springs				X	X	6					x	
Select Anti-roll bars				X	X	X	7				x	
Select Dampers and damper mounts				X	X		X	8	X	X	X	
Select Tires				X	X			X	9	X	X	
Select Bushings and body/frame mounts				X	X			X	X	10	X	
Measure Suspension and steering kinematics				X	X			X	X	X	11	
Set Steering friction & boost, suspension alignment				X	X						X	12

Tire/Bushing/Shock
Tuning Block

The final assembly and build checks typically do not result in iteration, but involve corrections to the build and assembly. Significant issues are addressed in later build phases. In some instances body and chassis hardware modifications are made to simulate a design change that occurs at a later build phase. This is due to the high level of difficulty and time required to correct body and chassis hardware issues.

Build Checks include the following:

Check body during hard points at assembly

- Measure tunable parts
- Verify part design level on vehicle
- Review structural integrity as vehicle is built

Final Assy Checks include the following:

- Check suspension components for looseness
- Verify fastener torques
- Verify ride heights
- Check and set suspension alignment
- Collect Kinematics and Compliance measurements & verify to design
- Verify suspension travels
- Check for chassis/bushing groundouts
- Neutralize all suspension, exhaust system, body/frame/engine mounts

The largest iterative block, tire/bushing/shock tuning, in some instances also includes spring and anti-roll bar selection. More than 100 iterations can occur before a solution is reached in this iterative block. Pre-tuning and tuning checks involve some of the following:

- Check and reduce friction in suspension and steering to meet system targets
- Set rotating mass imbalance to production specifications.
- Check steering and suspension components for lash, build quality and general integrity.
- Check tire pressures daily
- Repeat appropriate checks from Final Assembly list for every component change
- Use consistent vehicle loading

When prototype vehicles are dedicated to the tuning process some of the pre-tuning checks can be avoided, depending on the part changes involved. In instances where prototype vehicles are shared among development engineers, these steps need to be conducted. In some instances these checks do not occur due to the compressed schedule of the shared vehicles. This drives additional risk of more rework due to late rework discovery in the event of pre-tuning and vehicle setup issues.

Tuning DSM Insights: NVH and Vehicle Dynamics Interactions

Two vehicle dynamics tuning steps, tire selection and bushing & body/frame mount selection, can have significant effects on NVH attributes such as road noise, tire noise, and driveline NVH. The current process does not involve NVH in the initial selection of tires or bushing rates. Vehicle dynamics engineers use the program Product Attribute Leadership Strategy (PALS) to support tire and tuning bushing tradeoff experiments. NVH is typically called in if there are issues with the selected tuning such as unwanted tire noise. In many instances the only short-term NVH countermeasure is adding sound barrier and absorption material to the vehicle interior. This can result in significant cost and weight increases. This is due to the fact that changes to tires and bushings/mounts can cause significant rework, requirement revalidation, and program risks. Process improvements that involve NVH in the tire and bushing selection process will help prevent such issues. A step can be introduced into the tire selection process to identify the NVH opportunity of tire and bushing/mount selection. Such a step may involve running NVH experiments with the softest tires and bushings in the tuning kit and or running with a master set of tires without tread (slicks). The Vehicle Engineering management team will then be more informed with respect to the tradeoffs and opportunities involved in tire and bushing/mount selection at the earliest stages. Prescribing tire & bushing/mount selection early will provide the vehicle dynamics engineer time to rebalance ride, steering and handling using the remainder of the tuning parameters. This may also lead to fewer NVH countermeasures such as sound package that add cost and weight to the program.

The requirements and cascading process considers each attribute independently, while there is little documented in design guidelines and requirements to highlight and manage the attribute interdependencies. This can result in chassis system designs that are not optimized for both vehicle dynamics and NVH attributes, and the potential for large iterative loops and high levels of rework throughout the Product Development Process. The attribute interaction challenge is present in vehicles ranging from the smallest subcompact to the largest Sport-Utility vehicle.

<u>Summary</u>

This chapter provided an analysis of the automotive company at three levels of abstraction; the enterprise, the pre-program, and chassis tuning processes. The Enterprise and Pre-Program Approval <PA> processes were analyzed using an activity-based DSM while the chassis tuning process was analyzed using a task-based DSM. The next chapter will consider the next level of detail with the analysis of the chassis design using Axiomatic Design concepts.

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Introduction

Chapter 5 considered complexity at the Enterprise, Pre-Program, and vehicle development levels. This chapter takes the analysis of complexity to the next level of detail with the analysis of automotive chassis design. The axiomatic design concepts utilized for this analysis were presented in Chapter 4. This chapter summarizes the analysis and comparison of two suspension types using Axiomatic Design principles. The goal is to use axiomatic design concepts to improve the suspension design to achieve higher level of attribute performance for both the vehicle dynamics and NVH attributes.

The Challenge

Vehicle Dynamics and Noise/Vibration/Harshness (NVH) design requirements conflict in a number of ways. The vehicle dynamic tuning process goals include providing responsive steering and handling characteristics. In order to achieve the desired attribute performance, compliance of the chassis system is minimized. This typically manifests in bushings and mounting systems that have less compliance, which equates to increased bushing stiffness. NVH design requirements for the chassis system include the desire to achieve high levels of isolation. This high level of isolation is achieved through selection of bushing and mounting systems that are compliant. These compliant bushings isolate the cabin from unwanted road and Powertrain vibration inputs.

Coupling in Suspension bushing isolation and stiffness manifests through vibration levels and compliance as a result of road forces through the wheel and vibration generated by the driveline/axle. Axiomatic design concepts are used to reconcile the challenges of achieving functional performance of the chassis design given the challenges identified. Two rear suspension designs are assessed for their ability to provide both dynamic tuning capability and isolation from unwanted road and driveline vibration.

Method

A description of axiomatic design concepts was provided in Chapter 4. The rear chassis systems analyzed in this chapter have been in production for many years. Reverse engineering was used in the review of the systems and components under consideration. The design matrices that follow were developed by synthesizing insights gained from technical literature reviews, the author's knowledge of the interactions in suspension function, and subject matter expert consultation. The analyses are intended to provide a basic understanding of the methods that were used to go from the "what" to the "how" in suspension design. An **X** in the design matrix represents dominant relationships between functional requirements and design parameters, while an x represents a relationship that has a secondary effect. A 0 signifies relationships that have very little effect relative to the other factors.

Three-Link Solid Axle Design

Independence Axiom

A Design Matrix for a three-link solid axle suspension at the higher (parent) level using the Independence Axiom design principle is summarized in figure 34. Note the analysis considers the functional requirements for both NVH and Vehicle Dynamics attributes. The analysis demonstrates the highly coupled nature of the design of the three-link solid axle suspension.

Figure 34. Axiomatic Design Matrix for a Three-link Solid Axle Design.

Three-Link Solid Axle Suspension

			Design Parameters			
			DP1 Susp. Geometry / Kinematics	DP2 Susp. Compliance		
				DP2.1 Lower Link Bushing K	DP2.2 Upper Link Bushing K	DP2.3 Lateral Link Bushing K
Functional Requirements	FR1 Veh Dynamics	FR1.1 Ride	X	x	x	0
		FR1.2 Handling/Steering	X	X	X	X
	FR2 NVH	FR2.1 Road NVH	0	X	0	X
		FR2.2 Driveline NVH	0	X	X	X

FR1 & FR2 NVH and Vehicle Dynamics are Highly Coupled

Information Axiom

When the information content of the Three-Link design is considered from the Information Axiom perspective, a significant amount of "information" is required to satisfy the functional requirements. For example, the variation in functional performance for FR2.2 Driveline NVH is affected by DP2.1 lower link bushing stiffness, DP2.2 upper link bushing stiffness, and DP2.3 lateral link bushing stiffness variation. The result is higher functional complexity. For example, when the stiffness of DP2.3 lateral link bushing is decreased, the other paths (DP2.1 and DP2.2) can become most critical as the vibration energy of the source (axle) is distributed in a different way. This suggests that the range in bushing isolation performance as it relates to axle noise is affected by the ability of the design of each of the DP components to meet the target levels.

Independent Rear Suspension Design

Independence Axiom

The design matrix for an independent rear suspension at the higher (parent) level is summarized in figure 35. One of the strengths of the independent suspension is the introduction of additional design parameters (DP's) to make isolation parameters independent of suspension kinematics and compliance parameters. The analysis demonstrates a design that tends toward the decoupled design, with most of the strong interactions below the diagonal. This provides the opportunity for NVH and Vehicle Dynamics development engineers to develop the vehicle tuning with more independence, i.e., with fewer interactions and less probability of rework.

Figure 35. Axiomatic Design Matrix for an Independent Suspension.

DP3: Additional Design Parameters

Independent Rear Suspension

			Design Parameters			
					DP3 Stationary Mounts	
			DP1 Susp. Geometry / Kinematics	DP2 Susp. Compliance	DP3.1 Subframe Mount K	DP3.2 Axle Bushing K
Functional Requirements	FR1 Veh Dynamics	FR1.1 Ride	X	X	x	0
		FR1.2 Handling/Steering	X	X	x	0
	FR2 NVH	FR2.1 Road NVH	0	x	X	0
		FR2.2 Driveline NVH	0	0	x	X

Dominant NVH & Vehicle Dynamics FRs and DPs are Decoupled

Information Axiom

When the information content of the Independent Suspension design is considered, less "information" is required for each functional requirement, as there are fewer design parameters that can contribute in terms of performance variation. For example, the variation in functional performance for road NVH is dominated by the variation in the functional performance of DP3.1, Subframe mount stiffness.

Suspension Mount Design

The three-link and independent rear suspension design matrices considered suspension design decomposition from a high level, considering only the dominant effects of design parameters on functional requirements. The functional requirements and design parameters can be further decomposed to lower levels. This section outlines further decomposition of FRs and DPs for suspension mounts. The particular example is for the rear subframe mount, DP3.1 from independent rear suspension decomposition. The decomposition is performed at two levels. The first decomposition describes how the subframe mounts DP3.1 affect the functional requirements in the independent rear suspension system. The second decomposition considers the subframe mounts DP3.1 at the component level, in an effort to describe the component design.

First level Decomposition for DP3.1 Subframe Mounts

The functional requirement and design parameter decomposition was considered for the DP3.1 subframe mount in the case of the independent rear suspension. Figure 36 describes the dominant relationships among functional requirements and design variables. The design variables considered relate to the mount performance for the three translational degrees of freedom, X, Y, and Z.

Figure 36. Independent Rear Suspension Subframe Mount (DP3.1) Design Matrix: Mount Performance.

			Design Parameters		
			DP3.1.1 Bushing X Stiffness	DP3.1.2 Bushing Y Stiffness	DP3.1.3 Bushing Z stiffness
Functional Requirements	FR1 Veh Dynamics	FR1.1 Ride	X	0	x
		FR1.2 Handling/ Steering	X	X	0
	FR2 NVH	FR2.1 Road NVH	X	0	X

The independent rear suspension subframe mount design matrix demonstrates decoupling among functional requirements and design parameters for the dominant relationships. This suggests that selection of bushing parameters can be made in such a way as to achieve low stiffness for FR2 NVH and higher mount stiffness for FR1 vehicle dynamics through judicious selection of bushing rates in the X, Y, and Z direction. This insight is useful when determining the range of bushing rates to order in the initial vehicle development tuning set (task 1 of the Task-based Chassis Tuning DSM, Chapter 5). In typical independent rear suspension designs four subframe mounts are used. This level of decomposition does not consider the effects of relative differences among the four subframe mounts, which would be considered at a higher level of decomposition.

Second Level Decomposition for DP3.1 Subframe Mounts

The next level of decomposition of DP3.1 subframe mounts considers the properties of the mount that govern the X, Y, and Z stiffness rates that were considered in the first level subframe mount decomposition. Figure 37 summarizes the dominant relationships among functional requirements and design variables.

Figure 37. Independent Rear Suspension Subframe Mount (DP3.1.N) Design Matrix: Mount Properties.

Independent Rear Suspension Subframe Mount

		Design Parameters		
		DP3.1.N.1 Compound	DP3.1.N.2 Size	DP3.1.N.3 Shape
Functional Requirements	FR1 Static Stiffness	X	X	X
	FR2 Dynamic Stiffness	X	X	X
	FR3 Durability	X	X	X

At this level of decomposition the functional requirements relate to the subframe mount performance at the component level. The design parameters are made up of the mount properties that result in the mount component performance. DP3.1.N.1 considers the formulation of the compound of the polymer used in the mount design. DP3.1.N.2 considers the size of the mount. DP3.1.N.3 includes alternative mount design types, including the use of voids and stiffening plates. Note there is considerable coupling of the mount construction parameters. Durability requirements (FR3) and the properties of rubber (DP3.1.N.1) are among the governing factors that couple the static and dynamic stiffness of the mount. A mount must possess a given level of static stiffness in order to meet durability requirements. This static stiffness requirement along with the bushing size drives the selection of the material compound requirements. This analysis indicates that it is not possible to decouple static and dynamic mount stiffness.

Conclusions: Axiomatic Design

The goal of axiomatic design is to "establish a scientific basis for design an to improve design activities by providing the designer with a theoretical foundation based on logical and rational though processes and tools."[25] The tool attempts to reduce the seemingly random design search process, minimize iterative trial and error, and determine the best designs among alternatives.

This chapter demonstrates that axiomatic design principles can be used to reduce coupling of suspension design parameters to achieve a design that improves both vehicle dynamics and NVH attribute performance. The high-level suspension design matrices represent the design intent. Further decomposition was developed in order to facilitate execution of the design. The decomposition of functional requirements and design parameters from the suspension design to the bushing design levels aids the engineer in making design decisions at the lower level that are consistent with the high level design intent. In many instances this level of knowledge is present in the experts minds; the benefit of the concepts are in their ability to facilitate communication among experts and management in order to ensure that the knowledge is being used where it is required.

Conclusions and Recommendations

This thesis provided insights into the decision-making, design, and development processes in an automotive company, while presenting methods to assist teams solve problems that arise due to high complexity. The following provides a summary of the conclusions from the studies, recommended actions to address limitations in the design and development process, and opportunities for further study related to the work presented herein.

DSM and Axiomatic Design are Useful to Reduce Complicatedness

Automobiles are complex and complicated. Quick decisions that are not informed with the knowledge of the interactions can be costly. Interactions must be considered in the decision-making process to avoid the adverse consequences of decisions and eliminate "surprises" or adverse system emergent properties. The application of system engineering tools such as the Design Structure Matrix and Axiomatic Design concepts can reduce the increasing complexity and complicatedness in automotive design and development. While it is not always possible to uncouple functional requirements and design parameters in complex systems, the use of axiomatic design concepts facilitates dialog within the team and can lead to systems with reduced coupling. These methods make interaction information available when needed and provide a mechanism to preserve and accumulate systems knowledge, so that challenges can be addressed to ensure that the resulting solution resides along the efficient frontier of product design.

Start Simply

This thesis has demonstrated that DSM's and Design Matrices with matrix elements that highlight critical interfaces are useful to foster communication of issues relevant to the team organization and decision-making processes in product design and development. Identification of the "critical few" relationships that are dominant in system performance at the various levels of abstraction will align behavior and decisions to achieve optimal results at each level of abstraction. As the concepts and methods become second nature to engineers, more sophisticated applications can be developed. Prior studies have shown that methods such as the Design Structure Matrix and Axiomatic Design concepts have limitations in that they do not include the probability or strength of interactions. Such limitations require more sophisticated models that define the objective functions between interactions.

Manage Information Explicitly

This investigation highlighted the importance of information in automotive design and development. It is critical that the importance of information is recognized and managed. Individuals should be trained to recognize the importance of making the results of their efforts accessible, and skills should be taught and time allocated to allow individuals to seek out information related to their efforts. Information that is non-program specific should be identified and decoupled from the product development process to minimize the length of rework cycles. Downstream knowledge should be brought upfront. This can be accomplished by rotating personnel with downstream process and launch experience upstream to support new development efforts.

Account and Provision for Risks in the Development Process

Risks have to be taken and decisions have to be made without perfect information in automotive design and development. An understanding of the upfront risks should be accommodated by budgeting time and cost reserves commensurate with the risk in order to make a more informed and optimal decision when making program decisions early in the product development. Foster and provision for early iteration, when learning can occur at lower cost and to reduce the risk of changes downstream. The addition of low-cost workhorse vehicles to address platform capability and target-setting studies is just one approach.

Reduce Complexity and Complicatedness through Reuse

Reduce complexity and complicatedness in organizational, process, and technical domains through reuse. Each of the Design Structure Matrices presented herein demonstrate that each product development or design change has a significant "ripple effect" on other activities, attributes, and designs. The opportunity of change should be balanced against the cost of complexity vs. using existing systems.

Organize to Support and Foster a Systems Approach

Coupling of attributes/functional requirements and suspension architecuture/design parameters drives the need for an organization that fosters a systems approach in order to ensure that appropriate decisions are made at key stages in the product design and development process. Building competency of managers in Systems Engineering concepts and providing appropriate time, engineering, and financial resources to support the added tasks involved in upfront chassis design and development will lead to less rework and improved attribute performance downstream. Explicit interface meetings and interface documents should be established to increase dialog among stakeholders and clarify the interactions and impact of decisions on system performance.

Opportunities for Future Study

Axiomatic design concepts are useful for reducing coupling of functional requirements and design parameters in automotive design. While these concepts are useful to communicate differences among alternatives, the process does not include the impact to cost, which can be a key driver in architecture selection. A useful extension of this effort would be to develop an approach to integrate cost into the design structure matrix using one of the existing value engineering methods.

A second opportunity for continued research is in the area of identifying constraints in the Design Structure Matrix and Design Matrix interactions that, if released, would provide high leverage for the process or design. This would allow the team to develop and focus research on high-leverage challenges. An example related to the work presented would be in the area of bushing design. If a new material could be developed that would provide isolation of vibration at higher frequencies while maintaining desired static properties, it would result in great flexibility in chassis design and development to improve vehicle dynamics and NVH performance without requiring tradeoffs.

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Appendix A. A Simple System Dynamic Model of The Automotive Market: Ford Taurus

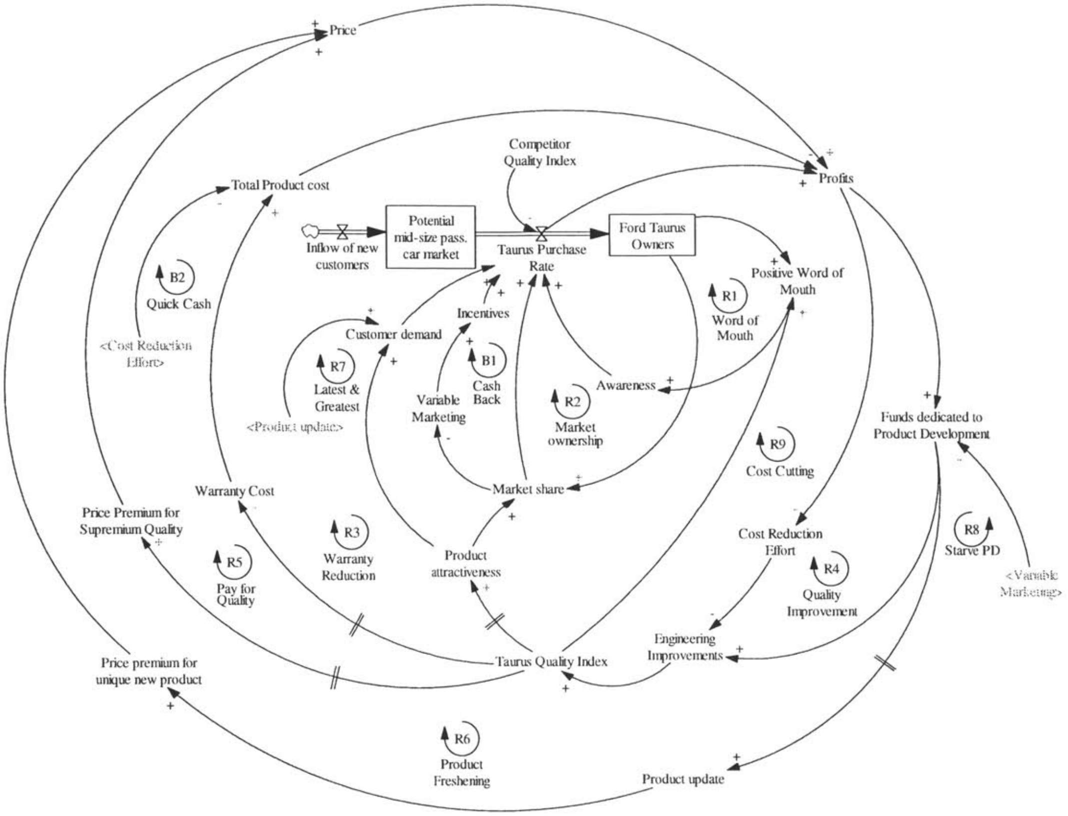
Introduction

The following provides an example of a system dynamic model of the automotive market for the Ford Motor Company Taurus vehicle. The model is provide to highlight the dynamic complexity in the automotive industry along with a number of the important reinforcing and balancing feedback loops.

Ford Taurus

Getting the product right is critical. The Ford Taurus was introduced in 1985 and was a market hit. By 1992, the Taurus was the number one selling passenger car in the United States with sales of 410,000/year. Since that time, sales have steadily declined to 325,500 in 2002, with approximately half sold to employees and rental or corporate fleets. Taurus has lost most of its sales to high quality competitors, specifically, exports. Many factors account for the loss of sales and market share including price, relative quality index in the market and frequency of product updates. Figure 38 details the system dynamics of Taurus sales and the feedback loops that reinforce the reduction of sales that have occurred.

Figure 38. System Dynamics Model for The Ford Taurus.



Reinforcing and Balancing Loops

Nine important reinforcing loops and two balancing loops affect the sales rate. Figure 39 describes the loops and their main effects. Also, the current relative strength of the feedback is assessed in the table.

Appendix A. A Simple System Dynamic Model of The Automotive Market: Ford Taurus

Figure 39. Significant Market Reinforcing and Balancing Loops for the Ford Motor Company Taurus.

Loop Description	Effect of Loop	Relative Strength of Loop
R1: Word of Mouth	New Taurus owners create positive/negative awareness of car due to word of mouth reinforcing more/less Taurus sales.	Low
R2: Market Ownership	As the Taurus market share increases/decrease, purchase rate increases/decreases and owners increase/decrease, hence, reinforcing the direction of market share.	Low
R3: Warranty Reduction	As profits increase/decrease, investment in quality increases/decreases, thus, reducing/increasing warranty costs (after a delay) which subsequently effects total costs and reinforces more/less profits.	Medium
R4: Quality Improvement	As profits increase/decrease, investment in quality increases/decreases yielding a delayed improvement/reduction in product attractiveness and reinforces more/less sales.	Low
R5: Pay for Quality	As relative quality in the target market segment increases/decreases, the delayed price premium for quality increases/decreases subsequently raising/lowering price and profit. The increase/decrease in profit affects the amount of quality investment and reinforces the direction of relative quality.	Low
R6: Product Freshening	As profit increases/decreases, product updates increase/decrease after a significant delay allowing increase/decrease in price premium for a fresh product affecting vehicle price and reinforcing the profit increase/decrease.	Low
R7: Latest and Greatest	As profit increases/decreases, the investment in product updates increases/decreases which increase/decrease product demand (delayed), hence, increasing/decreasing the purchase rate and reinforcing high/low profit.	Low
R8: Starve PD	Increasing/decreasing variable marketing reduces/increases investment in quality, hence, reducing/increasing attractiveness and market share, reinforcing variable marketing cost direction.	High
R9: Cost Cutting	As profit increases/decreases, cost cutting efforts increase/decrease which decreases/increases investment in quality, hence, reducing/increasing attractiveness and customer demand, reinforcing the profit direction.	High
B1: Cash Back	As market share decreases, variable marketing and incentives increase which increases the purchase rate and owner pool, hence, increasing market share.	High
B2: Quick Cash	As profits decrease, cost cutting efforts increase, thus, decreasing total product cost and increasing profits.	High

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