Application of System Design Tools to Integrative Product Development Process

by

Christopher David McFadden

BS Mechanical Engineering, University of South Carolina (2001)

Submitted to the Sloan School of Management and the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering
Master of Business Administration

In Conjunction with the Leaders for Manufacturing Program
at the Massachusetts Institute of Technology
June 2005

Signature of Author____

Christopher D. McFadden
MIT Sloan School of Management
Department of Mechanical Engineering
June, 2005

Certified by____

Daniel E. Whitney, Thesis Supervisor
Senior Lecturer, Mechanical Engineering Department

Certified by____

Janice Klein, Thesis Supervisor
Senior Lecturer, MIT Sloan School of Management

Accepted by____

David Capodilupo, Executive Director of Masters Program
MIT Sloan School of Management

Accepted by____

Lallit Anand
Chairman, Committee on Graduate Studies
Department of Mechanical Engineering

Application of System Design Tools to Integrative Product Development Process

by

Christopher David McFadden

Submitted to the Sloan School of Management and the Department of Mechanical Engineering on May 6, 2005 in partial fulfillment of the requirements for the degrees of Master of Science in Mechanical Engineering and Master of Business Administration.

ABSTRACT

Although Magna (a fictional name for an automobile manufacturer) demonstrates year-on-year improvement across new and refreshed vehicle programs, they continue to lag behind the industry average within the category of "problems per 100 vehicles" as measured by J.D. Power and Associates' Initial Quality Survey (IQS). This project is concerned with the development of tools which can be used to improve the characteristics associated with complex system performance – considered a major factor in providing customers with high quality vehicles. The primary toolset leveraged for this effort was Datum Flow Chain (DFC) analysis which is useful for mapping out complex mechanical systems and identifying sources of potential improvement. This toolset also provides a practical means of generating standard design architectures which can be used to inform future product designs. Several technical and cultural barriers had to be addressed in order to clearly demonstrate the value of this new approach to improving customer satisfaction.

Thesis Supervisor: Daniel E. Whitney, Senior Lecturer, Mechanical Engineering Department
Thesis Supervisor: Janice Klein, Senior Lecturer, MIT Sloan School of Management

ACKNOWLEDGEMENTS

I would like to begin by thanking the individuals who, through their patience and wisdom, supported me in my undertaking at Magna Motor Company. First among these must be my wife, Jennifer who has always been my biggest cheerleader and most stalwart supporter. Thanks for your willingness to endure a difficult relocation (actually two) and for the flexibility you demonstrated in adjusting your own plans and aspirations. I also owe a debt of gratitude to Dan Whitney and Jan Klein who have inspired me both in and out of the classroom with their life stories and sharp insights. I feel that I have learned so much from you both.

I would also like to thank my supervisor at Magna, Chip, for his support and direction and for his continued effort to lead change in a difficult environment. And of course, big appreciation goes to Eric McGill who experienced every one of my highs and lows as my office mate and fellow supplicant. Thanks for a great experience.

Finally, the author wishes to acknowledge the Leaders for Manufacturing Program for its support of this work.

CHAPTER ONE: PROJECT MOTIVATION

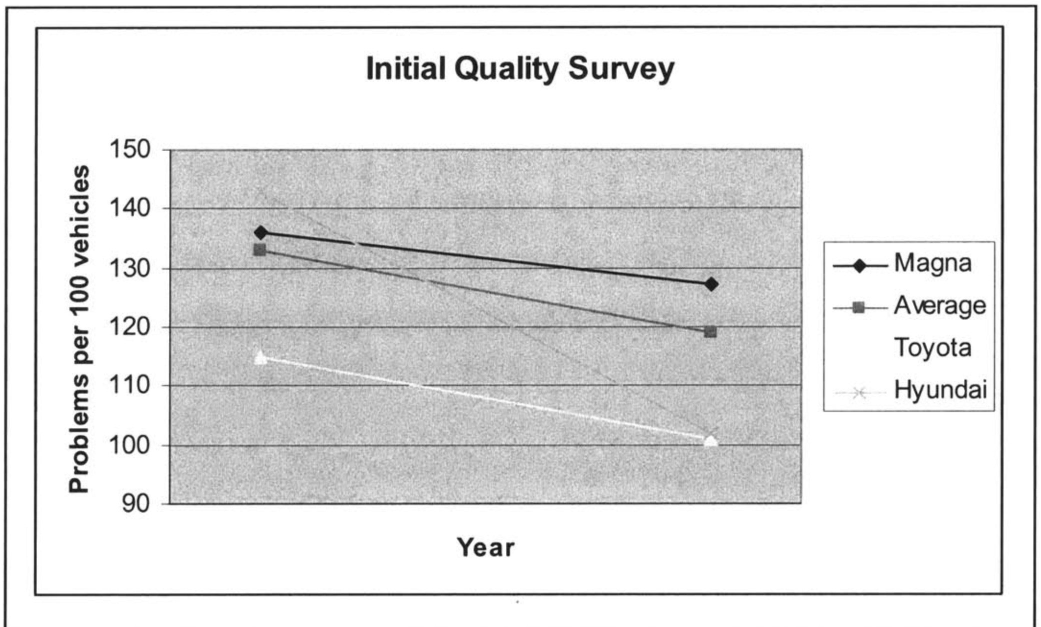
Introduction and Thesis Structure

This thesis seeks to present the work completed in fulfillment of a Leaders for Manufacturing (LFM) internship as performed on site at Magna Motor Company. The true name of the company has been disguised, as has been the names of individuals mentioned throughout. The first portion of this thesis will present the background and motivation for the internship project. This thesis will explore the nature of the current door closures system design issues as defined by Magna as well as actions taken within the company to remedy the situation. We will then consider the specific issues that affect the Magna-duty truck line (currently in production). Then, by examining the collection of tools currently in use, we will be able to identify technical and cultural gaps that can be met by the introduction of new techniques and new modes of thinking. Our attention will then turn to the use of Datum Flow Chain (DFC) techniques and their potential use within Magna. Finally, we will provide recommendations for Magna on the implementation and execution of these techniques.

Increasing Industry Competition

For more than 100 years, Magna Motor Company has worked to develop and produce vehicles that consistently meet or exceed evolving customer expectations. Although traditional indicators of quality such as engine performance and reliability of the major system functions remain critical to each program's success, an increasingly prominent role has been played by what the customer considers the "look and feel" of the vehicle. Each year, massive amounts of customer quality feedback is collected and analyzed in order to assess areas of necessary improvement involving this "softer" perception of quality. These collected data typically demonstrate that Magna, although an exceptionally competent automaker, generally lags behind the industry leaders.

One source of such data is J.D. Power and Associates, a group which generates reports such as the Initial Quality Survey (IQS), the Automotive Performance, Execution, and Layout Study (APEAL), and the Vehicle Dependability Survey (VDS). In particular, J.D. Power's IQS presents owner-reported problems in the first 90 days of ownership, a period in which "soft" attributes such as wind noise, water leaks, poor interior fit/finish and squeaks/rattles are particularly conspicuous. It is interesting to note that although Magna has continued to improve their perceived initial quality (which is measured in problems per 100 vehicles), they- along with other U.S. automakers – remain below the average industry quality levels. As shown in Figure 1-1, Magna's IQS 2004 performance came in at 127 problems per 100 vehicles for 2004. Although this represents a 7% improvement over 2003 results (of 136 problems per 100 vehicles) it must be contrasted with the 2004 industry average of 119 problems per 100 vehicles (which has fallen from 133 problems per 100 vehicles in 2003).



	Magna	Average	Toyota	Hyundai
2003	136	133	115	143
2004	127	119	101	102

Figure 1-1: Quality as a Moving Target

These results demonstrate the difficulty that Magna has had in meeting a moving quality target. In fact, Magna's ranking actually fell from 2003 to 2004, moving them from their position as the #7 IQS-ranked automaker to #8. Meanwhile, the newly re-emerged Hyundai Motor America has leapfrogged Magna by generating quality improvements of 30% over last year's results. The automotive landscape against which Magna has been struggling is likely to become even more competitive as auto manufacturers become increasingly adept at providing customer satisfaction.

Magna's success as a company, in the model years ahead, will depend in large part on its ability to anticipate and meet the increasingly refined demands of its customers.

As this thesis will explore, the delivery of a significant number of these customer attributes depends on a sound, systems-level understanding of the final assembled vehicle. As quoted from J.D. Power's Interior Quality Report, "the initial quality and appeal (design satisfaction) of new-vehicle interiors, is an area that is becoming a competitive advantage for today's manufacturers." In order to cultivate and maintain the integrative perspective necessary for success, Magna must continue to support current initiatives that promote the active involvement of knowledgeable personnel across functions and programs. In the time the author spent at Magna it became generally evident that the appropriate people (management and engineering) recognized the need for systems thinking and, were interested in improving. In addition, many of these individuals are looking for the right tools to help them get there.

Vehicle Wind Noise as a Motivation for Developing a Systems Approach

One example of just such a systems-level customer feature – which must be controlled within the context of a complex system – is that of vehicle wind noise due to aspiration. This aspiration had been a problematic source of customer complaints for Magna over the last several years and across a large number of programs. In general, complaints of wind noise can refer to a wide variety of occurrences, including component vibration and other motion induced at high vehicle speeds. However, for the purposes of this thesis, 'wind noise' will be considered synonymous with door aspiration – which can be described as the 'whooshing' sound due to the egress of air around the door seal. This phenomenon is caused by insufficient door-to-body sealing in the face of a pressure differential between the cabin and the environment. This noise typically occurs at higher vehicle speeds (which lead to a greater pressure differential) and is often more serious in older vehicles, whose door seals are more aged. Because of the nature of the seal's reduced performance, this noise comes on all at once and is quite easy to distinguish from other cabin noises. The occurrence of a given vehicle's wind noise can be characterized as a system problem because of the complex relationship that exists between this customer attribute and a host of others including door margin, flushness, and closing effort. This collection of attributes will be more fully introduced in chapter 2.

Seal Gap and Wind Noise Issues Associated with Magna-duty Trucks

As mentioned, wind noise has been a perennial complaint among drivers of Magna trucks, and feedback collected from customers and dealerships can provide clues concerning the factors involved. Anecdotal evidence suggests the enormous number and variety of factors contributing to any given vehicle's reduced customer satisfaction, as illustrated by the following customer feedback.

- <u>Dependence on user input</u> "If I close the door harder the wind noise gets much better." The way in which each customer interacts with his vehicle is a source of variance which may exacerbate vehicle performance - particularly performance associated with non-rigid or flexible geometries.
- <u>Dependence on ambient temperature</u> "It only seems to happen in the cold (40F)". Seal shape, size, and elasticity naturally vary with temperature.
- <u>Dependence on vehicle speed/direction</u> "I only noticed it at 40mph and above". "I noticed it only when going around curves". Although customers are correct to observe the effect that driving speed and direction had on wind noise, most are unaware of the causality that exists between an interior/exterior pressure differential and windnoise. This differential is itself caused by higher velocities. Additionally, driving through a turn places side forces on the door which may contribute to a seal's reduced performance.
- <u>Dependence on particular environmental events</u> "I Suspect wind noise due to water freezing in seal".
- <u>Dependence on system parameters</u> "It depends on cracks from other doors". As reflected to some degree in all of these customer comments, the notion that wind noise is a product of other inputs is critical. However, there is a demonstrated tendency for customers (or designers or assemblers) to oversimplify the cause and effect relationships and so neglect aspects of the system that are essential for success.

When comparing Magna's trucks against models offered by competitors, the same consistent discrepancies are noted. In the case of Body and Interior Quality data collected by J.D. Power, Magna's trucks show to be comparable to other U.S. automakers, but lower performing than the best in class. Rather, both of Toyota's 4-door truck offerings receive the highest possible rating for this category, which includes assessment of windnoise and other related factors (see Figure 1-2).

Rating	Make	Model	# Doors
★★★★★	Toyota	Tundra	4 dr
★★★★★	Toyota	Tacoma	4 dr
★★★★	Magna	Magna-duty	4 dr
★★★★	U.S. Auto #2	Sierra 2500HD	4 dr
★★★★	U.S. Auto #3	Ram 1500	4 dr

Figure 1-2: Rating of competitor's vehicles (trucks)

For its part Magna has recognized the significance of wind noise complaints and the importance to customers. Substantial customer research has shown a high level of correlation between a vehicle's interior quietness and the ensuing customer satisfaction. Because of this, Magna has recently begun to take steps towards better understanding and improving their vehicles along this dimension. Current initiatives include the development of metrics, the formation of teams, and the application of issue specific tools. In order to understand the impetus behind the internship project at Magna, it is first necessary to appreciate the effort which has been put into one particular initiative: the designation of internal Closure System Integrators or CSI's.

Role of CSI's in Delivering Customer Satisfaction

Recently, Magna has taken new steps to plug the gaps they acknowledge exist between engineering groups responsible for achieving related (but sometimes conflicting) product attributes. This initiative includes the formation of a new role – Closure System Integrator – which is responsible for success of vehicle closures across a variety of vehicle programs. At Magna, 'closures' refers to the parts of the car body that open and close, such as doors, hatches, lift gates, hoods and trunk lids. Engineers chosen to serve as Closure System Integrators become responsible for utilizing their cross-functional engineering expertise to establish key relationships between closures design engineers from various functions and programs. Although these CSI's are typically not given additional organizational authority beyond their engineering peers, they are unofficially considered the 'first among equals' when difficult decisions are required. The expectation is that many apparent design conflicts can be resolved by the determination of a solution found to be a mutually acceptable – preferably a global optimum. By empowering these agents to think beyond the confines of their various functional and programmatic stratifications, they are free to search for these creative solutions through the exchange of information and the exercise of quantitative tools.

Currently, CSI's fall into one of two categories. The first are those that report to the manufacturing side of Magna's organization (also known as vehicle operations) and are generally responsible for applying their engineering knowledge towards the anticipation and resolution of issues threatening the future manufacturability of a given program. Due to these engineers' experience with the details and difficulties of vehicle operations, it becomes possible to generate solutions to problems before they arise – through the early improvement of vehicles' design for manufacturability. Currently, the manufacturing CSI group is comprised of three engineers, each considered an expert from his/her respective area: stamping, body construction, and final assembly. This arrangement allows each to bring unique knowledge and experience to the resolution of complex problems, as they are co-located together. Just as importantly, it enables the team to leverage relationships which reach back into the depths of the automaker's divisions as the need arises. This team is led by a closure system manager (CSM), who likewise has considerable Magna experience and is responsible for setting team deliverables. He also allocates team resources to current vehicle programs as they request the team's expertise. This is often done by assigning a single team member to work for an extended duration with one or more vehicle teams.

The second category of CSI's are those that sit on the program development side and who are generally held responsible for achieving critical system metrics known as vehicle sections. Functionally, this group (generally known as the program development closure system integrators or PD CSI's), can be considered analogous to the manufacturing CSI's, except that they work further upstream within the process. These CSI's work with teams of program engineers to ensure that component design proves capable to meet assembly level requirements. Besides a difference in job function, several other important distinctions should be noted. For one, the PD CSI's are not co-located and in some cases, work within different buildings, making communication via phone, email, and weekly meetings essential. Also, the PD CSI's are considered much more intimately tied to a single program, for which they bear great responsibility. Finally, the team is considerably larger (approximately 9 engineers) and is not led by a closures system manager. Due to their involvement with the early design of programs, the focus of this thesis will be on this second set of CSI's.

Description of Internship Project

As developed by Magna, the project to be undertaken consisted of working within the aforementioned CSI groups to develop and demonstrate tools that would allow these engineers to more effectively diagnose and resolve systematic customer issues. This particular assignment was supported by several executives within the automaker, demonstrating that the need was real and acknowledged throughout the organization. A focus on analytical tools, and the way in which they could aid the exchange of information and the reformulation of organizational boundaries thus formed the crux of my work and will be the primary topic covered within this thesis. More specifically, attention was drawn to Magna's need to better design and control the parameters which influence customer attributes across all vehicle lines. However, rarely can one customer requirement be solved independently of many others due to the interrelated complexity of a vehicle system.

In order to understand the complex and interrelated nature of customer attributes, it was necessary to consider a group which share common influencing factors. Within vehicle closures, there was known to be a great amount of overlap among the following attributes: vehicle wind noise, vehicle water leaks, door closing efforts, door opening efforts, and door margin and flushness. However, it was not unusual for each of these attributes to be considered individually and optimized without adequate regard for the others. In this way, interaction effects – and other systematic complexities – have often remained undiscovered and unresolved. Because of this, a vehicle's demonstrated wind noise is best considered as one of a large number of deliverables which must be simultaneously provided. In recent years, automakers have become increasingly adept at system design. However, without the development and use of tools that better explore these complex relationships, it remains difficult to dramatically improve system performance, and hence customer satisfaction.

Thus, for the internship project, the use of two tools was considered in great detail; that of DVA (or Dimensional Variation Analysis), a tool already anchored and used at Magna, as well as DFC (Datum Flow Chain analysis) a new tool which has made inroads into the automaker but has not yet reached a tipping point. Improvements in the use of both of these tools were discovered, in light of their current use. Analysis from these tools was then used to make general design and organizational recommendations for Magna as it moves forward in its quest to deliver superior customer satisfaction.

Roadmap for Thesis

The general framework for this thesis consists of the introduction and exploration of Magna door closures and the development of tools for improved analysis. Chapter 2 presents the Magna door closure system and familiarizes the reader with key components and customer attributes that will be referenced later in the thesis. In Chapter 3, development of some basic systems thinking will take place before we move on to consider the current and proper use of Magna's current systems tools, including DVA (Chapter 4). The next section is then built around a thorough discussion of DFC tools and their proper construction, which is critical for understanding as the technique begins to see greater use within Magna (Chapter 5). Our attention then turns to the specific assembly techniques involved with the Magna-duty truck line and how they can be effectively modeled and analyzed using Datum Flow Chains (Chapters 6, 7). In Chapter 8 we consider the design recommendations stemming from the use of these tools, and what steps the automaker might take to improve its attribute delivery. The next chapter (Chapter 9) turns its attention to the ways in which DFC practices can be embedded with Magna for use on future programs. Finally, Chapter 10 presents the development of a DFC construction and analysis software intended to ease Magna's transition to the use of these techniques.

CHAPTER TWO: MAGNA DOOR CLOSURE SYSTEMS

Before we can explore the current and future application of system tools at Magna, it is important that we first understand the system which is the subject of our study. The term closure refers to all the various vehicle subsystems that involve the movement of parts to produce 'open' and 'closed' states, such as the car's hood, trunk, tailgate, and doors. Many factors are responsible for making these subsystems difficult to manage, particularly from a customer satisfaction perspective.

Door System Components and Hang Strategy

The closure system of concern for this thesis is that of vehicle doors. A brief description of each of the primary components is necessary, many of which are depicted in Figure 2-1, which shows a door closure system for a Magna-duty truck.

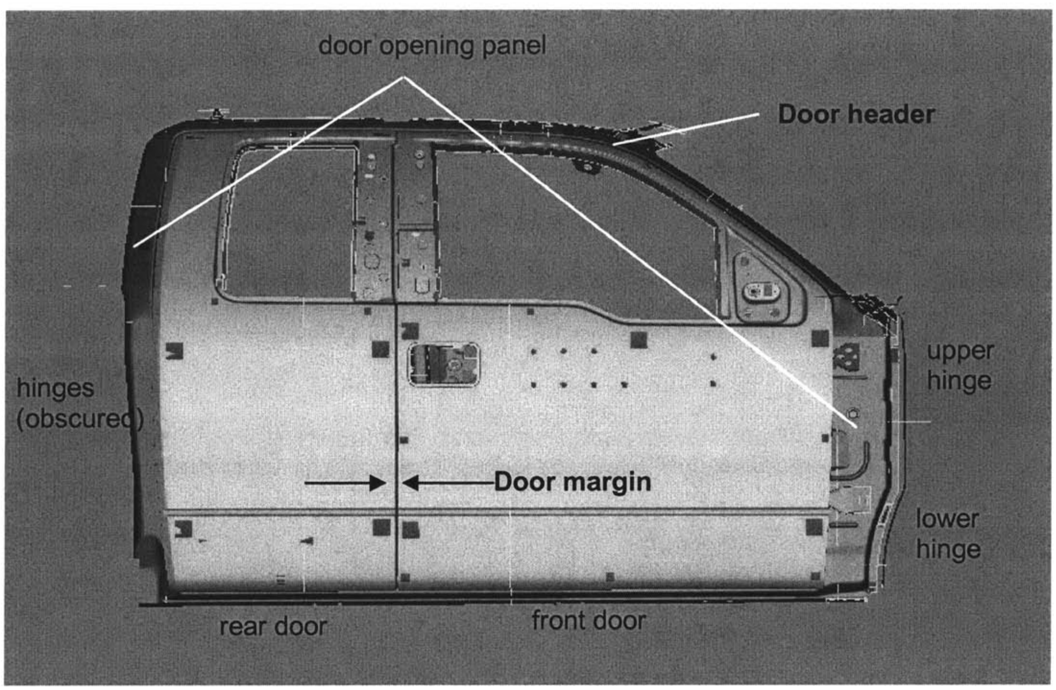


Figure 2-1: Truck Door Closure System

This particular vehicle has two doors (front and rear) each supported by two hinges (upper and lower). Since this design contains no pillar between the doors, the rear door's hinges are located towards the rear so that the door opens backward – opposite that of the front door. All four hinges connect the doors with the DOP or door opening panel which surrounds and frames the doors. The role played by the door header, which is the portion of the door above the window, is often critical to achieving customer satisfaction. Additionally, the presence of several layers of sealing (or 'weather stripping') can be noted along the door or DOP. Finally, the system's striker and latch mechanism work to keep the door closed. The body's strikers (not shown) are metal bars that engage with the door latches and catch to hold fast. In this system, the rear DOP contains two strikers that match to latches within the rear door, while the rear section of the front door contains a single latch placed to engage with a striker installed in the rear door. Because of this, the rear door must always be closed first.

The selection of each system component as well as its relative position and orientation is informed by the strategy that has been set for how the door is to be hung. This is known as a hang strategy. During the development of a program's final design, this strategy may evolve in an iterative manner as engineers work to satisfy design requirements. For this reason, a thorough understanding of the interrelatedness of each component is essential. Certain hang strategies such as the use of a NAB pin hinge with rocker tool can be expected to yield results that will be favorable to one or more customer attribute, as will be explored in future chapters.

Door System Attributes

Generally, a set of attributes for this system can be considered to include those listed below. Figure 2-2 depicts a cross-section of a closed Magna vehicle door looking in the area of the header and the DOP with two levels of sealing. As many of the salient customer features involve metrics associated with cross-sections such as these, the term 'vehicle section' is employed to refer to them. The figure below shows how some of the critical customer attributes are defined:

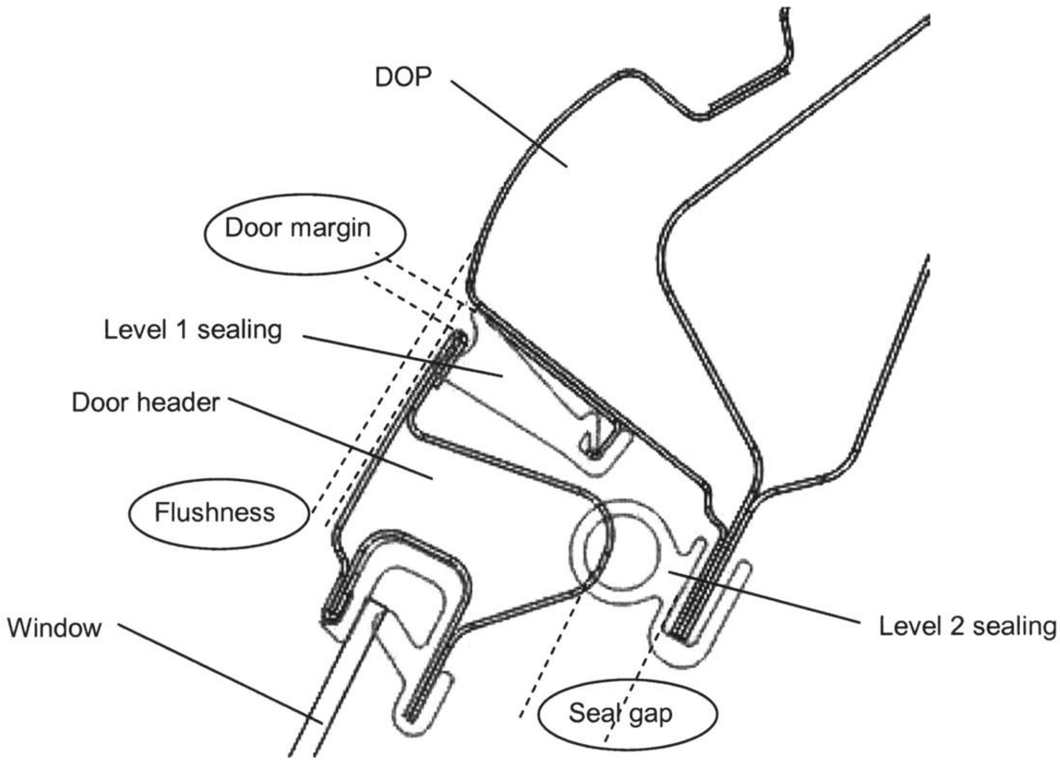


Figure 2-2: Cross-section of Closed Door

- Door Closing Effort (not shown): This represents the amount of force, and the duration over which that force must be applied, in order to completely close the door. This attribute is best understood as being the customer's overall satisfaction with the action of closing his/her door. If door closing effort is too high the customer experiences strain and frustration with repeated closings of the door and may cause the door latch to only partially engage the respective striker. Conversely, if door closing effort is too low, the customer will find himself 'slamming' the door unnecessarily hard. In extreme conditions, the door may 'close itself' if the vehicle is parked at even a slight incline. The feel of the door as it is closed has been found to convey product quality cues to the vehicle owner.

- Door Margin: Door margin is understood to mean the gap which surrounds each door and which is measured either from door edge to DOP edge or door edge to door edge. Achieving acceptable door margin means ensuring that this gap is consistent and of minimal size. Although door margin should be controlled around the entire door, the area of greatest concern is the space above the header since this is the margin that will be most obvious to potential vehicle owners.

- Door Flushness: Door flushness refers to the outboard alignment of door to DOP (or door to door) and can be qualitatively assessed by running your hand over the door margin and feeling for a change in the in/out position. Generally, doors should be set perfectly flush to the other framing components.

- Door Closing Sound (not shown): Many customers have shown a preference for particular sounds associated with the close of a car door. Although some of these preferences are obvious (e.g. lack of rattles or squeaks), others are more complex and involve the door sounding 'solid' upon closing.

- Door Water Leaks (shown as seal gap): This customer requirement consists of the door subsystem not allowing water to flow inside the vehicle once the windows have been closed, and depends heavily on the ability of the door to create a robust seal with the DOP and other door.

- Door Wind Noise (shown as seal gap): Door wind noise is an attribute which quantifies the loudness (in sones) of air egress while driving. As discussed in the previous chapter, this is considered a high priority customer attribute. The ability of the system to achieve acceptably low levels of noise is directly related to its ability to provide adequate sealing. The seal must fill the distance set by the seal gap, despite the various conditions the system will be subjected to, including aging, changing temperatures, and extreme pressure differentials between the inside and outside of the cabin. These conditions tend to affect the door's outboard position with respect to the DOP, often leading to door deflection which is sufficiently high to allow the egress of air. Figure 2-3 shows typical pressures seen by the closure system.

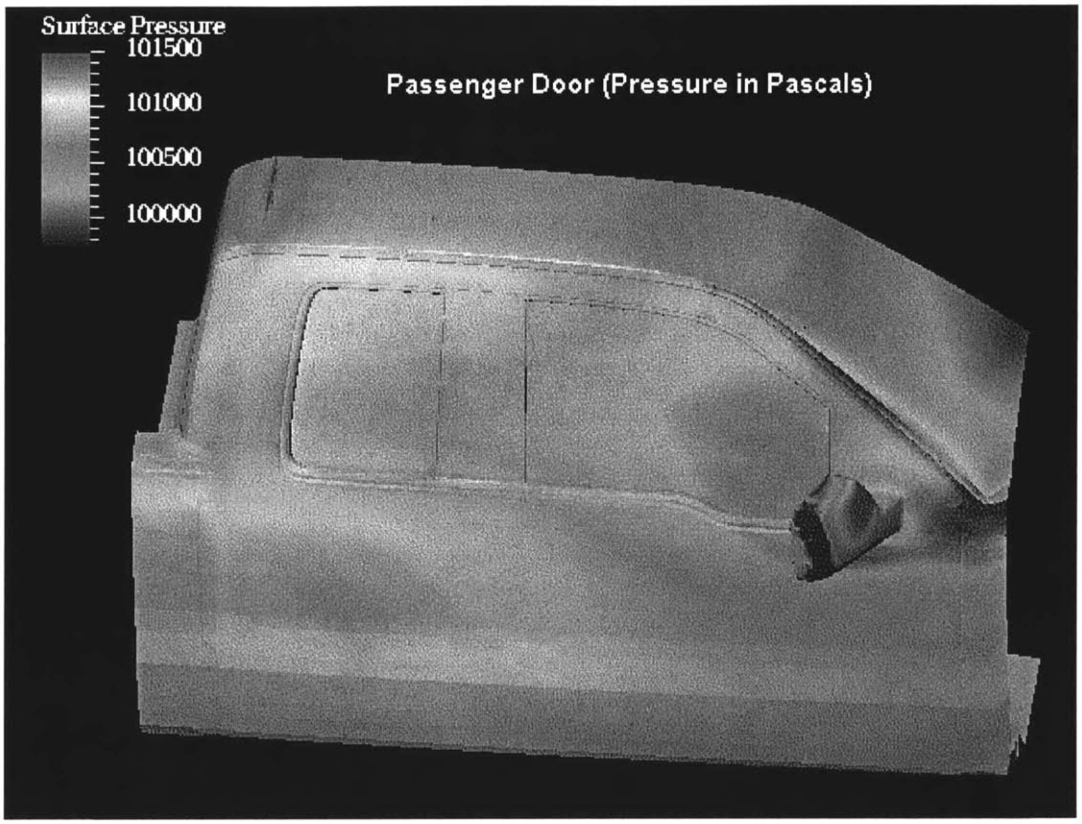


Figure 2-3: Surface Pressures Applied to Magna-duty Truck Closure System

Wind noise and its Relationship to Seal Gap

In practice, designing for a customer attribute such as wind noise is exceedingly difficult. One reason for this is the large number of external and environmental factors that influence the behavior of the sealing system. However, one method for increasing the robustness of the design to these effects involves decreasing the size of the seal gap relative to the sealing system. In this way, even as door undergoes outward deflection, it will prove less likely to allow the egress of air through the gap. This simplifying design method of minimizing seal gap is currently applied at Magna. Although this method does not suddenly give us an easy design parameter (the minimization of seal gap is a difficult requirement), it does provide a method of limiting our design work to geometric relationships and allows us to be less concerned with the external factors. Studies have been performed assessing the relationship between a vehicle's seal gap and the door deflection (shown in Figure 2-4). This work has demonstrated the tendency of vehicles with smaller gaps to experience decreased door deflection when subjected to real world conditions. The figure below shows a Magna truck's door deflection at a simulated 100 mph highway speed. Trucks with smaller initial gap sizes demonstrated less deflection and less wind noise as a result. Because of the reasonableness and widespread practice of substituting seal gap as a proxy for wind noise, this thesis will consider seal gap size as the customer attribute of interest.

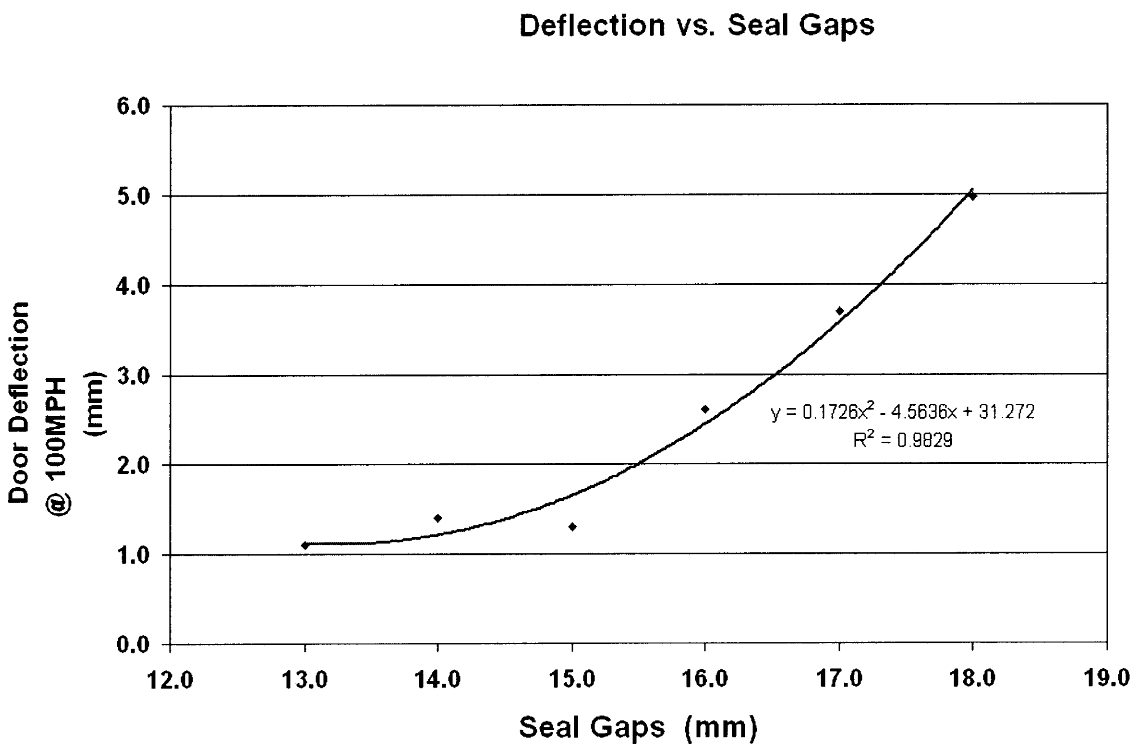


Figure 2-4: Higher Door Deflection for Larger Initial Seal Gaps

In line with the results shown above, Magna CSI's have found that doors may rotate outwards (as a semi-rigid body, within minimal flex) when these high speed pressure loads are applied.

Having provided background on Magna's door closure systems, it now remains for us to consider the nature of the complexity found in these systems before we turn our attention to the application of system tools.

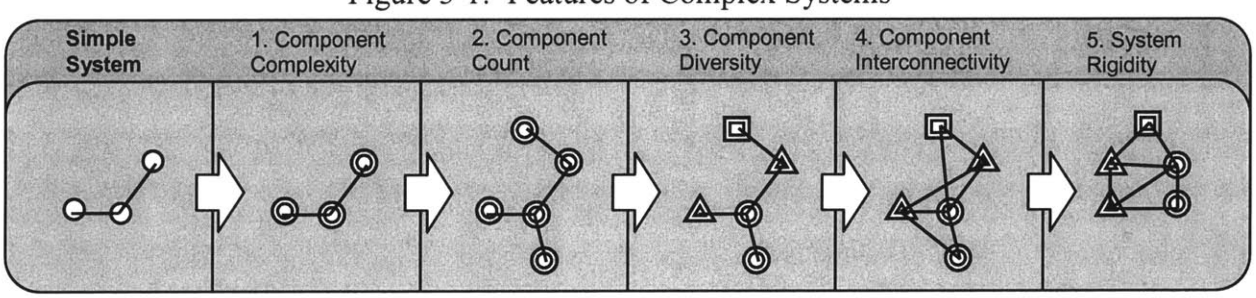
CHAPTER THREE: AN INTRODUCTION TO SYSTEMS LEVEL THINKING

Mapping of Complex Systems – Motivation for a Tool-Driven Approach

It is obvious to those within the automotive industry that any given vehicle represents a complex assemblage of designed components. Less obvious is the level of complexity required by the engineering tools applied to understand and improve such a system. Such tools have traditionally been seen as a means by which to improve the designer's insight into how he/she might modify an existing design – leaving the ultimate decision making authority to the discretion of the most knowledgeable engineer. Tools, then, play a critical but subordinate role to intuition; informing but not mandating a given approach. As system complexity continues to increase, intuition and experience must play an increasingly smaller role in the final design of vehicles. Instead, data driven tools capable of solving simultaneous deliverables while satisfying a vast number of constraints, must become more prevalent.

For our purposes, the definition of a complex system [from Magee and de Weck] will be taken as: *a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change* There exists a wide variety of such systems, which can be described by features of their behavior such as the number and diversity of elements, or their interconnectivity. Figure 3-1 represents five of these categories.

Figure 3-1: Features of Complex Systems



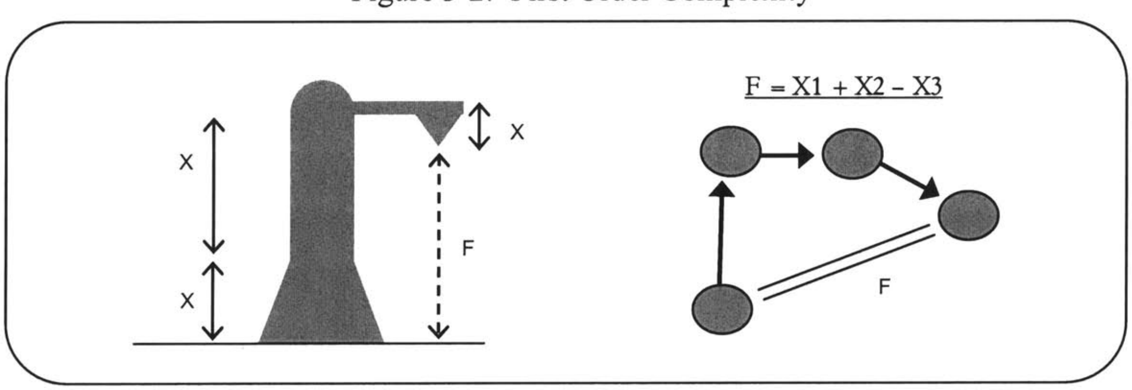
The system may be complicated by the level of intricacy associated with each of the subcomponents which comprise it. Similarly, the number of components involved within a defined system may serve to add a level of complexity, as might the range of design of each of the included pieces – and the differences they bear with respect to one another. Component interconnectivity can also vary widely depending on the construction and purpose of the system and may diminish the benefit of segregating and analyzing sections of this system independently. Finally, every system is subject to structural constraints – and must be constructed in such a way as to ensure each element is properly oriented with respect to the remaining elements. As a system's complexity increases along these (and other) dimensions, it becomes increasingly difficult for the human mind to develop intuition concerning the patterns of cause and effect flowing from that system.

Three Categories of Complexity

As Magna is in the business of designing and assembling systems, it is useful to consider the extent to which human intuition – even that of trained technical employees – is capable of managing complexity. As a simplified first attempt, engineered systems can be thought of as falling into one of three categories: first order, second order, or irreducible.

First order systems refer to those that can be regularly satisfied by modification of a single factor at a time. These are the simplest of the three, often requiring a minimal level of insight into the behavior of the components, and are the most common of the systems found in daily life. Such a system can be seen in an assembly where designed components combine to control a single overriding feature as seen in Figure 3-2. Examples of real first order systems include an office chair whose height adjustment handle independently controls the position of the user along one dimension, or a heavily secured front door which, in order to be opened, must undergo a series of sequential modifications, including the sliding of a chain lock, the spinning of a deadbolt, and the twisting of a door handle.

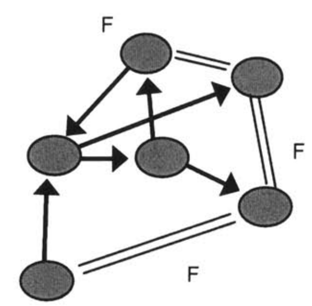
Figure 3-2: First Order Complexity



Second order systems are defined as those which attempt to satisfy multiple (often conflicting) attributes which fundamentally relying on the arrangement of the same set of components. For these systems significantly greater knowledge must be obtained before any modifications or improvements can be achieved. This is due to the potential of disrupting system attributes unintentionally or (even worse) unknowingly. In the case where a component may be serving 'double-duty' for two or more deliverables, but is not faced with an intrinsic conflict, optimal solutions may be found to satisfy the desired system state. However, when conflicts do exist, the need for tradeoffs should be anticipated and the relative prioritization of system attributes must be performed. Due to the multiple simultaneous objectives of these systems, and the difficulty faced by the designer who is trying to 'keep his eye on the ball', it doesn't take a large number of interrelated elements for traditional intuitive approaches to quickly bog down. Figure 3-3 shows a representation of a second order system. Examples of these include the band of a watch, which must be loose enough for comfort, but tight enough to hold fast, or some aspects of an automobile's internal combustion engine which must provide sufficiently high power for driving, while minimizing consumption of fuel and noise (among others).

Figure 3-3: Second Order Complexity

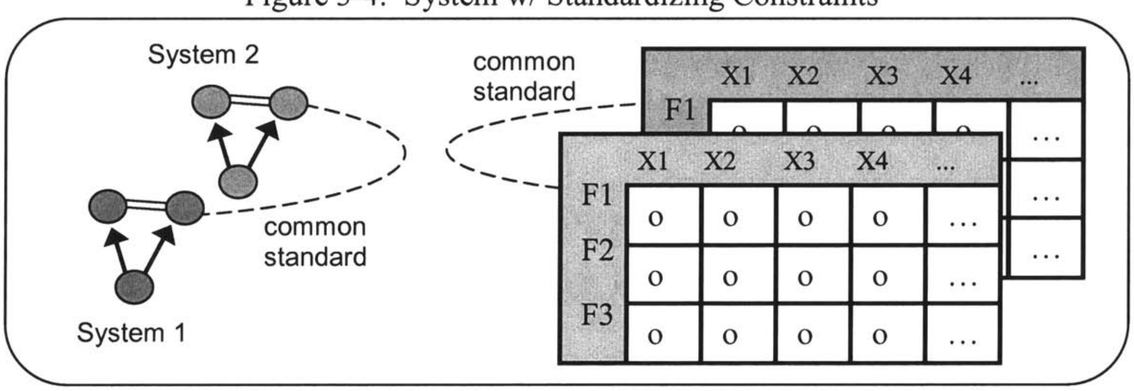
	X1	X2	X3	X4	X5
F1	o	o			
F2		o	o		
F3	o		o		
F4		o		o	o



The third category of system includes those with a high level of constraint across elements due to imposed standardization of common component designs. This category, known as irreducible, is a relational design with standardized constraints and occurs when the modification of a system's critical components is restricted due to the impact such changes would have on other components which share the same standard, but are otherwise indirectly related. An example helps to clarify this system. Consider the electrical cord of any household appliance. As the homeowner goes to plug this appliance in, he finds that the cord's electrical prongs don't quite mate with the wall outlet. This misalignment can be remedied immediately by deformation of the prongs to match the slot spacing of the outlet – allowing the system to achieve its function. However, should the fault lie with the outlet then the corrective action just taken will prevent the appliance from matching with the remaining wall outlets in the house. Before component modification occurs, it must first be determined which design standard has not been achieved. In general, however, it is not possible to alter the design for a single product (so designated as irreducible) without likewise altering the related design of an array of other products.

Ultimately, it could be argued that every component and subsystem that ever has or will come into contact with one another are all constituents of the same encompassing system. However, the creation of this third category allows systems to be considered independently while retaining the interdependence they share based on a common, standardized design. For Magna, these standards govern several of the design activities. For example, one requirement established by standardization is that every truck door be produced identically in order to match with any one of the identically produced truck bodies. Although in reality these doors will never be part of the same system, they influence one another indirectly through the establishment of common standards and management decisions such as whether or not to employ functional build strategies. Similarly, as a standard door hinge emerges for use across multiple programs, the freedom of any system or platform to modify its components is diminished. This category of system, which is governed by cross-program constraints, is depicted in Figure 3-4.

Figure 3-4: System w/ Standardizing Constraints



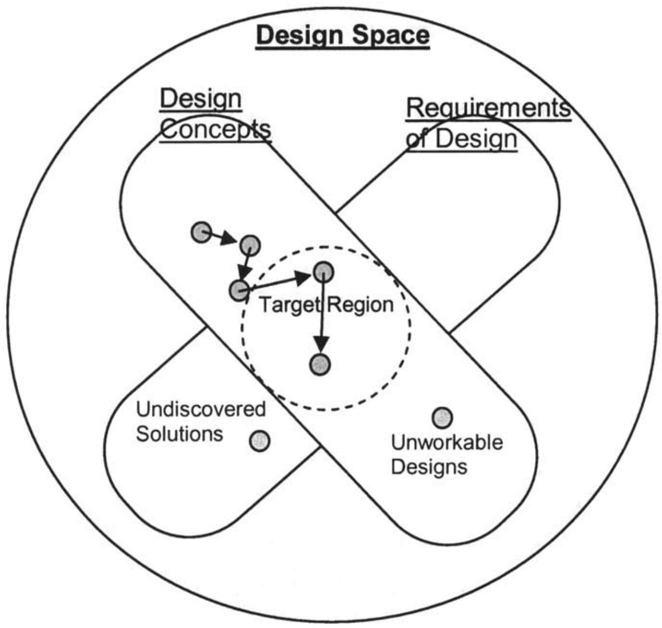
The Use of Systems Tools for Optimal Design

Recognizing and categorizing systems as being of first order, second order, or irreducible complexity should not be seen as mere exercise but as a means to match the need with the tools appropriate to solve it. Even in cases where a system, or collection of systems, cannot be cleanly defined using this methodology, it remains critical that engineers responsible for design strategies begin with these concepts in mind. In so doing, it then becomes possible to identify the gaps between what the current state of engineering tools can achieve (these tools include among them the human mind and its capacity to visualize and understand complexity) and what they need to achieve in order to continue organizational improvement.

Practically speaking, once a system has been categorized, it is then necessary to determine how tools may be developed or applied to take the burden of excessive complexity off of the shoulders of the designers. Although Magna has made use of a variety of toolsets in order to improve vehicle quality, it remains to be seen whether these tools will remain sufficient in an increasingly competitive marketplace with an increasingly complex product. Unfortunately, tools currently in place are insufficient to properly design systems requiring second order complexity or to thoroughly inform the strategies governing designs which cross a variety of programs – as is the case with Magna's current push for standardization.

Instead, tools at use at Magna generally show themselves to be excellent for optimizing simple systems or for breaking complex systems down and delivering sequential analysis. Without the use of sufficiently capable tools, design solutions that may improve the product line will remain hidden. Figure 3-5 demonstrates these 'undiscovered solutions' which may provide optimal achievement of design requirements, but which cannot be located by current tools. Acceptable designs are those which occur at the intersection of established design concepts which are known to exist, and those designs which fulfill all necessary requirements. As shown in Figure 3-5, Magna designers often begin the process with solutions that do not fulfill the full range of system requirements. The onus is then on them to iterate until the resulting design concept does satisfy the requirements. Although current methods often prove adequate for determining a 'good' design, they may not be capable of discovering every solution, and therefore potentially leave the optimal solution undiscovered.

Figure 3-5: Failure of Tools to Uncover Solutions



This next chapter will consider the use of system tools in place at Magna. These tools are currently employed to iterate the best reasonable design and have different uses within the organization. By presenting a brief introduction to these tools, we will then be able to move to recommendations for the improved use of system tools.

CHAPTER FOUR: USE OF SYSTEM TOOLS AT MAGNA

A senior leader at Magna is known for having said: "If you give engineers good tools they will use them." The truth of this statement can be debated, but it is at least evident that engineers who have insufficient tools to aid them in system design will produce designs that are lacking. As might be expected of a company as large and organizationally complex as Magna a large number of tools go underused (or unused) due to lack of awareness or concern. As this project is concerned with the development and recommendation of improved tools for system-level vehicle design, it is reasonable to first assess which tools have been historically used and are of great familiarity. The primary goal of this chapter will be to demonstrate the inadequacy of current tools to delivery engineered systems of the highest customer quality. In the following chapters, our thoughts will be turned to a tool that has more recently been developed but has not yet been used to Magna's full advantage.

The Current Use of Limited System Tools

Engineers at Magna have made proficient use of a number of tools as means of diagnosing and solving issues associated with systems. Included among these are computer aided tools such as CAD (computer aided design), FEA (finite element analysis), CAM (computer aided manufacturing) and CAE (computer aided engineering) as well as physical modeling tools such as Rapid Prototyping and Royalite models. However, in the gaps that exist between these tools, Magna engineers have demonstrated the tendency to patch their work using significantly less sophisticated tools such as the worksheets used to keep track of iterations on vehicle section requirements.

Each of these traditional tools has unique limitations, which we will not fully explore here. However, it is worth noting that each of these tools is generally employed in such a way that local incremental improvements are sought without regard to the impact of the assembly as a whole. The use of CAD and CAE tools serve as an example of these tools' limited ability to deal with second order complexity.

An engineer such as CSI who is responsible for ensuring achievement of a program's vehicle sections, is constantly in need of means by which to measure the current expected value, and to make alterations. By relying on CAD models of a targeted vehicle, it is possible for a CSI to quickly determine the numeric value of a particular assembled dimension. For instance, he can use the file's 3D data to 'measure' the seal gap that the model shows exists between the virtual door and the virtual truck body. In this way, tracking any single critical characteristic is relatively easy. However, should this value not be appropriately centered within the expected dimensional range some redesign of the underlying components or else a new assembly strategy becomes necessary. The CAD model – which merely represents the parts as currently designed – offers little assistance on how best to go about this design work without negatively affecting related attributes. Thus the engineer may be left to a sort of frenzied trial-and-error approach in order to meet his section requirements by the deadline.

The CAE tools used at Magna can generally be considered robust but less than perfectly exact when used in the analysis of a system's response to manufacturing and environmental variation. Often CAE is used to morph the existing surrogate design into the new, desired shape. However, these tools are far from perfect and have been known to yield results discrepant from the "real life" behavior of the system. One example of this discrepancy between CAE results and actual behavior can be found in a recent CAE study contrasting hang strategies employed in Magna doors and in Vega (another disguised automaker) doors for various vehicle models. The CAE model predicted superior performance of the Magna doors for wind noise and other categories. However, the Vega door was found to better achieve the targeted performance metrics, based on a side by side comparison of assembled vehicles. This deficiency is not yet entirely understood, but is due in part to the software's inability to correctly model the simultaneous inputs expected from a real environment. Similarly the tool is not adept at capturing the impact of system parameters on the various vehicle subsystems which may in turn influence any given attribute. Thus we see related behavior between the CAE and CAD systems, both of which begin to break down as system interdepencies go unregistered.

The widespread use of non-computational tools should also be briefly considered. These include checklists, worksheets and paper-based matrices which may find use in lieu of more complicated software packages and suggests some level of engineering dissatisfaction with the available collection of tools. One example of this is the PD CSI's target matrix which is used to manually record the value of an attribute (e.g. seal gap) as it changes. These changes in seal gap come about as design engineers are asked to modify their designs in order to meet the section requirement. As progress towards this section requirement is continually made, the matrix is updated. Similarly, the use of a 'parameter sheet' by CSI's helps to generate section targets, part tolerances and anticipated stack-ups and is considered to be good for team collaboration. Within manufacturing groups, a prioritization matrix may be employed to rank the 'relative importance' of conflicting attributes. This is then used to make ultimate decisions about which attribute should be 'favored' if the need for equipment adjustment arises. This use by Magna engineers of primitive heuristics to make decisions affecting customer satisfaction represents a break down in the availability of solid, effective tools. The need for better tools is obvious to many and the automaker has begun to take steps to improve their situation.

Second Order Systems Tools in Use at Magna - DVA

In addition to the tools already discussed, there is at least one other which has taken root within the organization and which offers significant advantage to the engineers and teams that are proficient in its use. This tool is known as Dimensional Variation Analysis (DVA). It is worth considering the current use of DVA in order to understand the gaps that remain today in the use of system-level tools.

Introduction to Dimensional Variation Analysis (DVA)

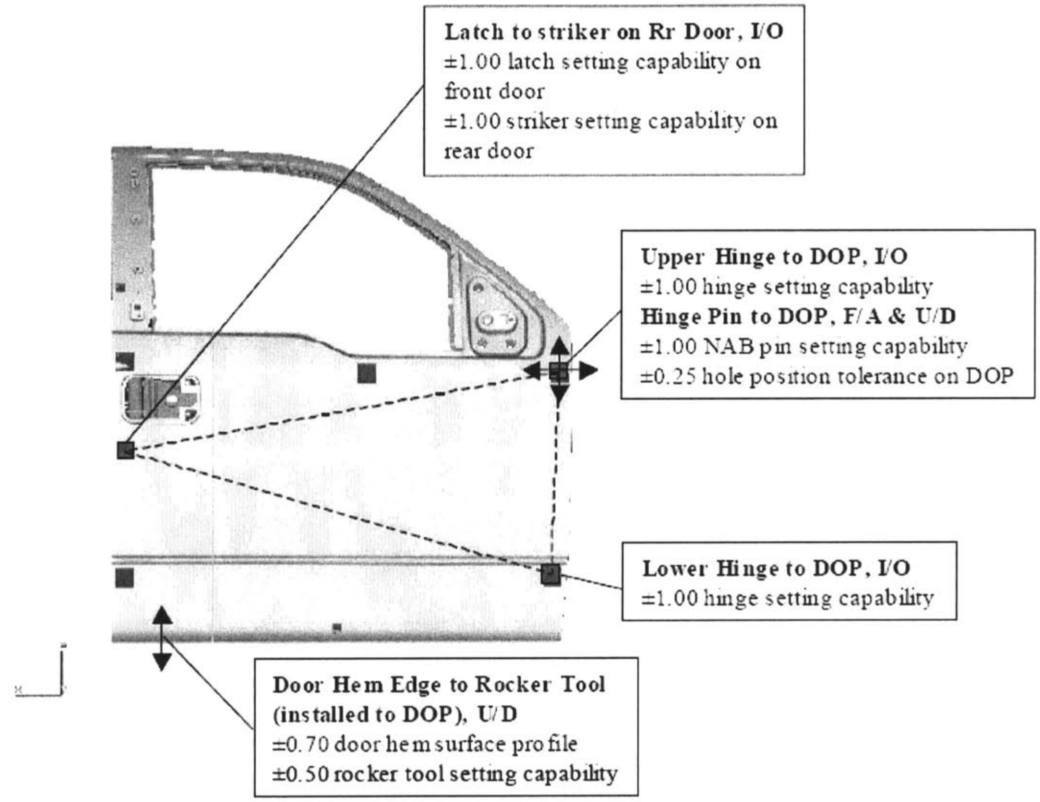
Dimensional variation analysis has been in use for decades at Magna, but remains poorly understand and underused. Using geometric CAD data for vehicle components, the DVA group is able to perform Monte Carlo analysis by varying the position of each component within its prescribed tolerance in order to view the resulting geometries of the final system. This is considered the primary function of DVA analysis and is typically performed by request from program manufacturing groups as problems are encountered related to product launch. Less often, DVA verification may be requested midway through the design process to ensure that vehicle section deliverables are achievable. The DVA group responsible for these analyses is small, independent, and found in Magna locations throughout the world (including England, Germany, Brazil and Australia.

Current Use of DVA

Today, DVA is considered a post-mortem design tool. Design will alter its model and then apply DVA to see if it works. Because of this, DVA influences design but does not inform it. Often the insight drawn from this analysis comes too late to be of much help – by this point the strategies are too far developed to be rethought. Rarely, the techniques of DVA might be requested very early in the design phase, before CAD data has replaced the 'cocktail napkin' sketches. Such up front collaboration allows those knowledgeable about the impact of component geometry to have a voice in the choice of strategy. In fact this is exactly the way members of the DVA group prefer the tool to be used – in order to save work and minimize missteps from Design. As one DVA employee told me, "I predicted this problem a year ago but no one listened". The reason for the limited use of this group and its set of tools stems in part from a lack of familiarity with the capabilities available through their use. Additionally, a general preference among some programs to decide their own strategies coupled with the possible backlog of work; prevent the design group from seeking out additional (possibly time-consuming) feedback until absolutely necessary.

DVA Outputs and Results

When properly used, DVA is capable of producing a variety of useful results. These include calculation of expected means and deviations of geometric customer attributes (e.g. seal gap dimensions) as well as calculation of necessary component and assembly tolerance based on the desirable mean and range for the final customer attribute (in effect working backwards). In addition DVA is capable of identifying major contributors of final assembly error (deviation from mean) in order to help focus attention on the appropriate sources. This is done through a high-low-median analysis in which transfer functions are generated and supplied to design teams. The rigidity and stability of the system are also computed through the use of the software. Finally, the output from a run can be used to generate transfer functions for Six Sigma black belts. For an example of a DVA run on the Magna-duty truck closures, see Figure 4-1 below.



	Measurement Location	Seal Gap Target (per Carl Zaas, P221 Closure Supervisor)	Est'd Variation, ±3-sigma (Iteration #1)	Est'd Variation, ±3-sigma (Iteration #2)	% Reduction in Est'd Variation
1	Front of Frt Door, A-pillar	±2.50	±2.69	±2.60	3%
2	Front of Frt Door	±2.50	±3.27	±3.19	2%
3	Rear of Frt Door	±2.50	±3.53	±3.46	2%
4	Front of Rr Door	±2.50	±2.83	±2.74	3%
5	Rear of Rr Door, Top	±2.50	±2.33	±2.22	5%
6	Rear of Rr Door, Above Glass	±2.50	±2.18	±2.07	5%
7	Rear of Rr Door, Below Glass	±2.50	±1.95	±1.81	7%
8	Frt Door to Rr Door, Above Glass	±2.50	±3.77	±3.64	3%
9	Frt Door to Rr Door, Below Glass	±2.50	±2.27	±2.04	10%
10	Frt Door to Rr Door, Beltline	±2.50	±2.09	±1.83	12%
11	Frt Door to Rr Door, Bottom	±2.50	±2.21	±1.96	11%
12	Frt Door at Top Hinge	±2.50	±1.95	±1.83	6%
13	Frt Door at Bottom Hinge	±2.50	±2.03	±1.90	6%
14	Rr Door at Top Hinge	±2.50	±1.90	±1.77	7%
15	Rr Door at Bottom Hinge	±2.50	±1.94	±1.82	6%

Figure 4-1: Magna-duty truck DVA analysis for seal gap

Figure 4-1 presents a CAD file for a typical Magna-duty truck and considers the critical points of connection. In order to ensure that the seal gap at each of the measurement locations (for instance #1 Front of Front Door at A Pillar) falls within an allowed tolerance, the deviation introduced by subcomponents and subassemblies is combined. This yields an estimated variation within which 3 sigma of assembled trucks are expected to fall. However, some simplifications are present in this analysis which may lead to larger errors than predicted by the analysis. One example is the conventional treatment of a door as a rigid part, or as two rigid parts (one above and below the beltline). In reality, flex associated with the manufacture and assembly of this door may introduce additional variation.

Technical Objections to DVA

Although DVA is a powerful tool for systems-level analysis, there exist some barriers to its optimal use. One of the current issues involves the occasional use of incomplete CAD models to perform DVA analysis. Although the development of CAD data does not fall under the DVA's group sphere of control, they ultimately own the output of their analysis and are held responsible for inconsistencies. Similarly, for DVA runs performed for manufacturing groups, data collected from the shop floor is routinely found to be sufficient but not entirely complete. Minor details concerning the manufacture may be lacking including the order of assembly or the presence of minor deviations due to manufacturing. Because of these and other limitations, even those DVA runs that are taken to completion may not lead to beneficial program changes.

DVA does not readily give engineers a method to directly influence design, but instead allows them to check the current design for predicted discrepancies. One reason that its use cannot ensure a properly designed vehicle is that it is not yet capable of analyzing the effect of fixturing and tooling on the manufacture of the final parts, nor is it able to consider the assembly sequence or the necessary manufacturing details (such as the slight taper on a thermoformed pin necessary to remove it from a mold). These limitations are technical in nature but could be improved upon by clearer lines of communication between manufacturing groups and DVA. In many cases the DVA groups are expected to work only from the design drawings (or models) for components instead of also gathering data concerning the manufacturing processes. As a result the analyses performed by the DVA group will blindly use the 'print' tolerances range as they are received from the design group – although rarely do these ranges mirror reality.

Although the full Monte Carlo simulation dynamically varies every contributing sub-component in order to obtain a true distribution of a system's final state – the HLM (high-low-median) Monte Carlo does not. Instead, this simulation – which is responsible for generating the "contribution effect" of components for engineers – applies a linear approximation and varies only a single component at a time. This means that some interaction effects may not be captured and so may result in some overlooked system relationships. Apparently no problems have yet been reported due to this simulation limitation. Presumably any interaction effect not captured in the HLM run will have been noted in an earlier full Monte Carlo. Although none of these technical limitations constitute a reason to abandon the use of DVA, they do help to explain the lack of support among engineers.

Figure 4-2 gives an example of the contribution spreadsheet as provided to engineering. This sheet is one of the more useful outputs of the DVA process and allows design engineers to understand the quantitative sensitivity of a given attribute to the design of the underlying system. By making alterations to the design strategy, the sensitivities associated with each component change. The use of this contribution spreadsheet enables the design engineer to work backwards, by asking how changes to the sensitivities might improve the desired outcome – and then how design strategies can be modified to accommodate this. Similarly the tolerance for each feature of each critical component can be varied to reflect potential manufacturing or design improvements. Ultimately, the goal of the engineer is to ensure that the appropriate customer characteristic is met within a three sigma range of assembly. Estimated Variation (shown in the figure) is found by applying the RSS method to the computed Effective Tolerances above, and allows iteration of values until the target tolerance is achieved.

Contributors	Sensitivity	Orig Tol (+/-)	Rev Tol (+/-)	Eff. Tol ±3 Sigma	Eff. Tol (HLM) (+/-)	Effect
FRT RH - 02 - RH FRT	2.428	0.70	0.70	1.699	1.699	28.48
FRT RH - 01 - RH FRT	2.376	0.70	0.70	1.663	1.663	27.28
5420124.02 MS, x	2.428	0.42	0.42	1.020	1.020	10.25
5420124.01 MS, x	2.376	0.42	0.42	0.998	0.998	9.82
FRT RH - 10b - MP,	1.000	0.70	0.70	0.700	0.700	4.83
RH - 04a - MS,	0.783	0.70	0.70	0.548	0.548	2.96
FRT RH - 03a - MS,	0.783	0.70	0.70	0.548	0.767	2.96
outer - 18b - MP,	1.000	0.50	0.50	0.500	0.500	2.47
5420124.01 MS, y	1.037	0.42	0.42	0.436	0.436	1.87
5420124.01 MS, z	0.721	0.60	0.60	0.433	0.433	1.85
5420124.02 MS, y	0.946	0.42	0.42	0.397	0.397	1.56
Tol - Hng NAB Pin, Y	0.770	0.42	0.42	0.323	0.323	1.03
			Estimated Variation	3.109	3.155	
			TARGET TOLERANCE	**2.00**		

Figure 4-2: Contribution Effects

Conflicting Perceptions on the use of DVA

Those Magna design and manufacturing personnel familiar with DVA appear to be of two minds concerning its use – there are those with high expectations for its capability, and there are those who have been disappointed by its use. These diatomically opposing responses can be attributed to the perceived role of dimensional variation analysis – which is to provide accurate and final quantitative results. Due to the limitations cited above, the results of any DVA analysis must be received tentatively and with regard to the process used to arrive at them. For this reason, it is the method of approach offered by the DVA, and not its numeric outputs, that should be considered its primary advantage. This third perspective of the tool must still require analyses to be performed correctly – but should be even more interested in the insights that can be captured by its application.

Recommendations for use of DVA

Although a study of the current use of DVA uncovers a number of key technical recommendations for its improved use, the most critical advice applies to the culture surrounding and communicating with the DVA analysts. The method of approach practiced by the DVA analysts and engineers, and their understanding of the intricacies of system design, were fundamentally sharper than those of their counterparts within the Magna organization. This is a credit to the years of practice they have had gathering data from each and every involved functional group within Magna and the time spent determining the systemic effect of changes to components. This resulted in the ability of the DVA analyst to 'hold his own' in several meetings I was privy to, where he debated design intent with program engineers. Despite their lack of in-depth knowledge concerning the various nuances of each program's design, the DVA analyst's ability to relate final system attributes to the condition of components or features was uncanny. By contrast, the design engineers often found it difficult to understand the many inputs to a system design since they did not have the necessary information from other groups. The first and overarching recommendation then is that Magna work to develop similar thinking within its own engineers while making greater use of those within the DVA group. This means not simply issuing more requests for analyses, but rather making members of this group active partners earlier in the design process. Moreover, it is recommended that design engineers and CSI's spend time performing DVA analyses on their own sections – and working to gather information and compare notes with other functions whose components prove critical to the delivery of customer attributes. The thinking that has been cultivated by the use of DVA within Magna will prove useful as the organization practices the use of DFC (Datum Flow Chain) techniques which are particularly well equipped to provide the necessary language and methodology for complex systems analyses.

From a technical perspective, several recommendations should be mentioned.

1. First, a typical analysis may only trace the relationships between a final customer attribute and a set of sub-assemblies. Instead, additional insight could be gained by following these relationships the entire way back to the constituent sub-components. This would also allow more extensive communication to design engineers involved in the earliest stages for the most fundamental components.

2. In a similar fashion, the tool might be used to establish intermediate assembly attributes. These attributes would be separate from those expected of the final assembly to meet customer expectation. Rather, these intermediate attributes would provide a nearer term target for design engineers, who may have difficulty designing a sub-assembly without a clearly understood and identifiable metric in mind.

   This could include the establishing of a quantifiable intermediate target for an engineer responsible for the design of a hinge as it relates to a door opening panel. For example, instead of working to meet the vehicle's ultimate door-closing effort design requirements, the engineer might work to meet a requirement governing the position of one or both door hinges. With a minimal amount of effort it may be discovered that certain interim values are simpler and more intuitive to manage.

3. It is recommended that the DVA group develop closer relationships with engineers involved in fixtures, tooling and general manufacturing decisions. Although ultimately, the flow of critical information should be seen between *design* and manufacturing groups, DVA analysts could greatly improve the accuracy and usefulness of their models by collecting the necessary data and strategies themselves, and then working to flow that information to design.

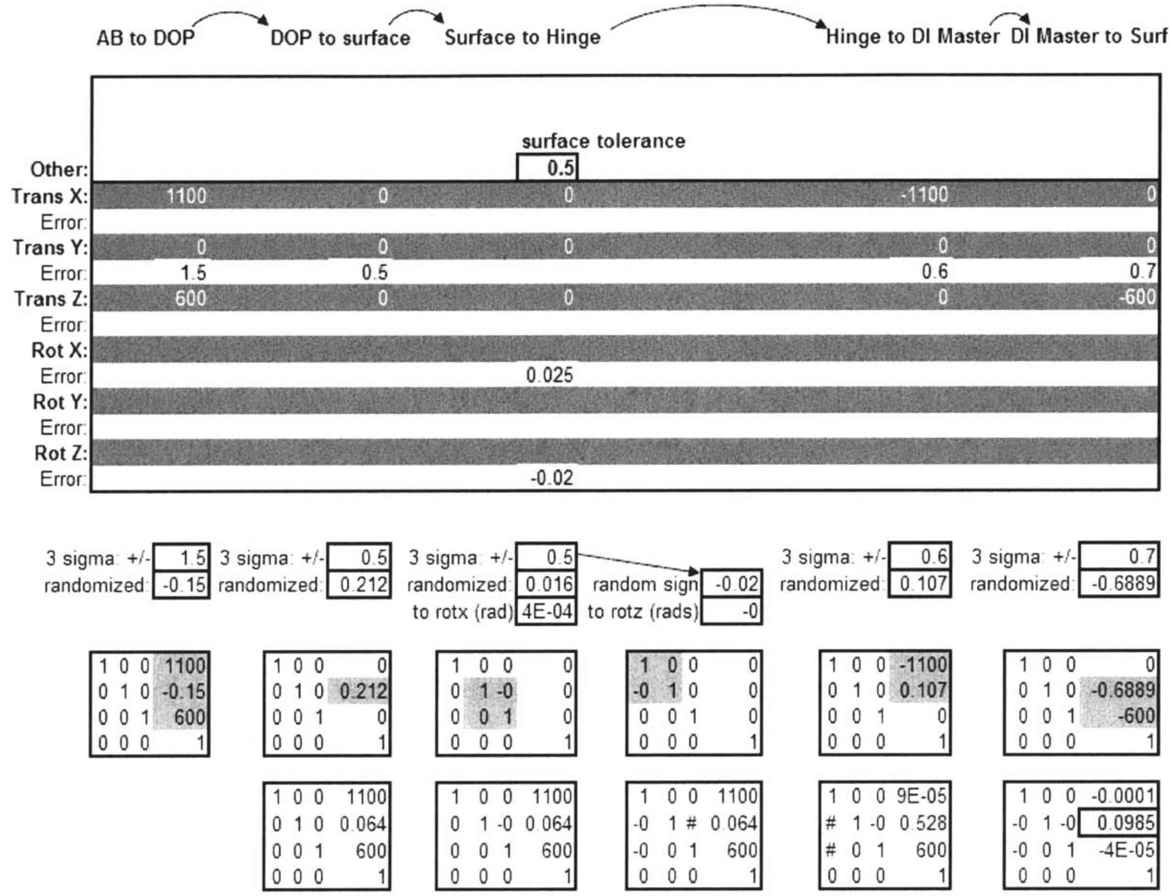
4. The further refinement and enhancement of DVA tools is also suggested. The core tool (VisVSA) is solid and capable of expansion. Several ideas for added functionality spring to mind, and include the ability to have the analysis directly compare two competing strategies, the ability to perform sensitivity analysis, and the ability to update critical input data dynamically from a central source. Fortunately, these types of improvement seem to be underway already, as demonstrated by the latest software release – a release which allows the user to model non-rigid bodies.

5. Finally, it is recommended that Magna develop expertise in the use of tools associated with DVA – particularly that of Monte Carlo – within their own design engineering group. This can be accomplished in many ways. One option is to train on the use of VisVSA,

which can be accessed by most engineers and used on most computers. Another possibility is to train engineers in the use of simpler software which can be run before the CAD data for a single part has been generated – and can be used to test a given design strategy. The development of a simple Monte Carlo simulation through an off-the-shelf commercial software package such as Decisioneering's *Crystal Ball* would provide Magna engineers the opportunity to generate instantaneous results on these important design decisions.

Figure 4-3 below shows the development of a simple Monte Carlo simulation using only Microsoft's *Excel*. This model allows the user to vary geometric inputs in order to verify a final dimension of importance. As shown, the propagation of position and error can be thought to flow from a given starting point such as the AB line, to the door opening panel (DOP) to the hinge, to the door inner master to the final door surface. At each point the translation and rotation are considered along with other component descriptions such as surface tolerance.

Figure 4-3: Simplified Monte Carlo for Verifying Dimensions



Importantly, this analysis does not require complex part geometry – merely the location and relationship of critical locators and linkages. The first table represents the location and tolerances associated with features and which can be pulled off of a 'back of the envelope' sketch. The matrices at the bottom represent the transformation of coordinates from datum to datum and allow the construction of a single continuous chain linking components to characteristics, using theory from Whitney's *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development.* [Whitney] This level of simulation could easily be adopted by key design engineers or CSI's in order to provide quick and reliable feedback to proposed designs (or design changes).

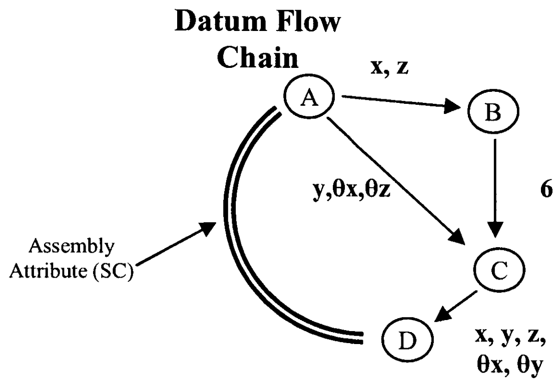
As an increasingly larger percentage of design engineers are made aware of the proper use of systems tools, it will become less difficult to develop products that satisfy a number of interrelated requirements. The continued growth and improvement of these tools will require the attention of senior management and the recognition that certain groups (such as DVA) already have a solid approach to complex design.

Datum Flow Chain (DFC) Mapping

One tool recently made available to Magna is that of Datum Flow Chain (DFC) mapping. This tool has been earlier introduced by Michael Gray and subsequently by Craig Moccio in their study of complex systems at Magna where it has begun to find application to product development [Gray], [Moccio]. The techniques of DFC can be used to graphically represent the linkages which exist within a product assembly and to perform analysis useful for distinguishing between designs that are more and less robust. DFC provides advantages over the techniques demonstrated by DVA due to its simpler and more intuitive approach for informing design – one that is accessible to a wide range of users and does not require the use of complex CAD tools. Additionally, the analysis that is available through DFC serves as a powerful complement to DVA. The concept of Datum Flow Chain analysis comes from Daniel Whitney and his book *Mechanical Assemblies* is considered the authoritative work on the subject [Whitney].

The visual representation of components and assemblies is accomplished using a collection of nodes and connectors to map the relationships. As shown in Figure 4-4, each DFC sketch will have a complete set of these elements, with each connector labeled according to the types of constraint provided. Each attribute or characteristic is represented by a double line and is labeled to relate it to a known customer attribute. Building on relatively simple concepts, the DFC yet possess great analytical power and is useful for identifying states of component constraint, potential conflicts of key characteristics, and other essential information. Due to this project's focus on the potential use of DFC tools at Magna, the next chapter is devoted to the subject.

Figure 4-4: Simplified Datum Flow Chain



CHAPTER FIVE: USE OF DATUM FLOW CHAIN (DFC) TOOLS AT MAGNA

Introduction to DFC Terminology and Techniques

In its simplest form a DFC represents individual parts as zero-dimensional shapes (nodes) which are connected by a series of one-dimensional linkages (liaisons). These liaisons express the extent of location and constraint passed to each node from previous nodes. Location and constraint may occur along or about 6 independent degrees of freedom (DOF): X, Y, Z, Tx, Ty, Tz, (as shown in Figure ?). Location of a part involves 'setting' its position in three-dimensional space while constraining that part involves holding it fixed along the dimension of interest. A component which is located and constrained along X has a determined position along this axis and is not free to slide in a positive or negative direction along it. A simplified rule set governing the construction of DFC's involves the following steps:

1. Construct nodes to represent every component of interest within a given system
2. Dedicate one of these nodes to serve as a base node. This node is considered to be fixed in space and is responsible for originating constraints involving other nodes.
3. Beginning with the base node construct liaisons between nodes to show the flow of constraints from part to part. These liaisons should be shown as arrows to indicate the direction of flow
4. Critical attributes involving the relationship between two components should be represented by a KC (key characteristic) which may be shown as a double line. These KC's are typically defined as geometric relationships between parts which are essential to meeting customer or internal measures of quality. In that capacity they can be regarded as measures of customer satisfaction.
5. Perform various design analyses on completed construction, depending on user needs.

A simple example of a DFC may help demonstrate their construction and general form. Later some time will be spent considering the methods of analysis available.

Hinge on Panel Example

An application of DFC can be seen in the following figures. Here the relationship between a hinge and a mounting surface is explored by deciding on the system boundaries and decomposing the assembly into its constituent parts. Figure 5-1 shows the CAD data taken from the Magna-duty program and orients the two-piece hinge to show its relationships to the NAB pin as well as the body panel to which it will be attached.

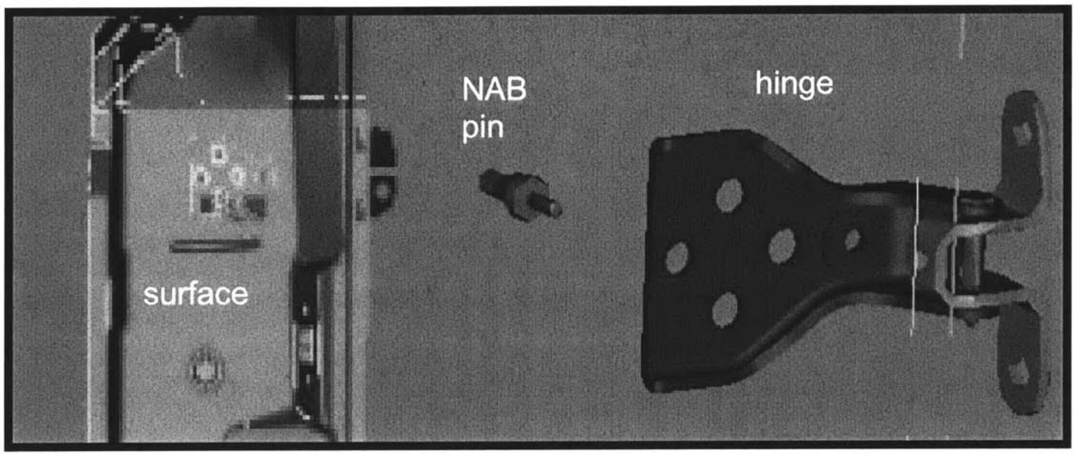


Figure 5-1: CAD Model of Magna-duty Front Door Hinge and Body

The hinge in this system is composed of two halves (labeled C and D in Figure 5-2) which interface to a sheet metal panel using a NAB-pin/hole strategy. The NAB pin (or No Adjust Build) strategy is commonly used across many of Magna's programs as means to locate the door hinge (and ultimately the door) to the vehicle body. The NAB pin which is labeled as part B is fixed to the hinge prior to assembly and interfaces with the hole within panel B.

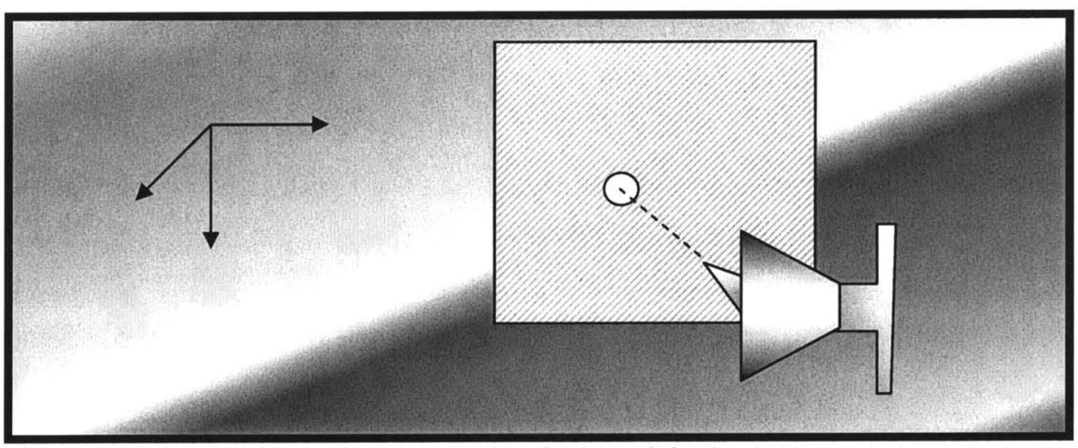
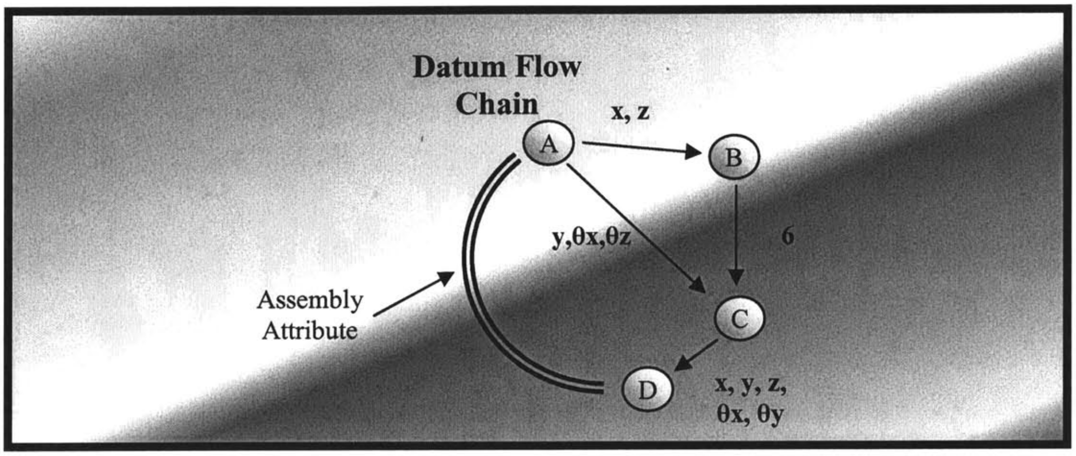


Figure 5-2: Simplified Model Diagram

If Figure 5-2 can be considered a simplified diagram of Figure 5-1, then Figure 5-3 shows the decomposition and representation of the system using only DFC elements. In order to understand the assignment of labels to each of the DFC linkages, it is first necessary to develop a system of assigning appropriate constraints.

Figure 5-3: DFC Representation of System



Assignment of Constraints

For the construction of this DFC, the vehicle body is assumed fixed in space due to its prior assembly on to the supporting and underlying components. The DFC shown in Figure 5-3 demonstrates the way in which constraint is passed from the panel to the other components. For the assignment of constraints to liaisons between two parts, the relative motions between the two must first be determined. A liaison only reflects those DOF that have been relatively constrained and does not reflect information involving other parts or constraints.

A to B: From A to B, the two constraints passed are along X and Z (we presume the pin to be a tight fit within the corresponding hole). In other words, after assembly of these two components, B will no longer be free to move in either of these two directions.

A to C: As the NAB pin slides into the hole, the surface of C rests against the surface of A, resulting in the constraint of three of C's DOF's: Y, Tx, Tz.

B to C: Since we are treating B as fixed to C (assembled beforehand), then B can be described as constraining all 6 DOF of C relative to itself. However, as mentioned above, B itself is only constrained in 2 DOF.

C to D: C constrains D in 5 DOF leaving free only motion about Z. This is due to the hinge joint linking the two which permits rotation about its axis.

Assignment of Customer Attributes (KCs)

For the purposes of this example, the relationship between the car body panel and the second hinge half is considered critical to quality. A number of reasons for this can be imagined including the effect this geometric relationship may have on the effort required to close or open the door. This attribute is shown by the double line in Figure 5-3 Once the attribute has been identified and described it is possible to perform a number of analysis.

Analysis of Constraint State

One measure of design performance can be taken from the constraint state of critical components or attributes. Generally, one would expect a fully assembled product to ensure that each subcomponent is fully constrained (and neither over or under-constrained) throughout the product's operation. Exceptions to this should be intentional and designed in, and are evident by a correct read of the fully constructed DFC. The basic process for checking a part's constraint involves ensuring that every one of the degrees of freedom has been fully constrained relative to the base part (or any other ground). Since each liaison establishes only the degrees of constraint between the two parts connected, the full constraint state for any individual component may only be assessed by 'tracing' the constraint state back through each supporting component to the originating part. For any one of a component's degrees of freedom that degree must be constrained consistently from supporting component to supporting component such that if any liaison along the pathway does not constrain a DOF, that pathway cannot be considered to lead to the constraint of the target component (for the DOF in question).

For a complex DFC the process of determining a component's constraint state can be difficult and time-consuming (and so will require an automated algorithm). However, analysis of the current example is given via the use of Figure 5-4. For this DFC, the constraint state of greatest interest is that of part D, since this will also be the constraint state of the critical attribute between A and D (since A is taken as fixed). In order to correctly determine D's constraint, both pathways must be considered; A-B-C-D as well as A-C-D. Figure 5-4 is used to assess the constraint state associated with each liaison, an 'x' signifying that the constraint has been captured. The summary listed at the end of the table shows that pathway A-B-C-D results in the constraint of X and Z while A-C-D results in the constraint of Y and Tx. This final row (labeled 'Cumulative') is determined by placing a constraint only if it has been assigned to every relationship preceding it. This is intuitive since should one of those relationships not provide the constraint, that freedom of motion will be passed on to other elements in the chain.

Figure 5-4: Table used for verifying DFC Constraint State

A-B-C-D	**X**	**Y**	**Z**	**Tx**	**Ty**	**Tz**
A: fixed	x	x	x	x	x	x
B: from A	x		x			
C: from B	x	x	x	x	x	x
D: from C	x	x	x	x	x	
Cumulative:	**x**		**x**			

A-C-D	**X**	**Y**	**Z**	**Tx**	**Ty**	**Tz**
A: fixed	x	x	x	x	x	x
C: from A		x		x		x
D: from C	x	x	x	x	x	
Cumulative:		**x**		**x**		

From this it is easy to see that our part D (the second hinge half) is under-constrained in both Ty and Tz which can be confirmed by examination. The second hinge half will remain free to rotate about its axis (i.e. rotation about Z) and the entire hinge will continue to freely rotate about the NAB hole axis (i.e. rotation about Y). This first under-constraint is sensible, if the customer is expected to be able to freely open and close the vehicle door. However, the second under-constraint is not acceptable and must be established by the use of a tool used to set the doors' proper Ty position. Figure 5-5 summarizes a number of values that may be important to a designer, including the state of over and under constraint for critical sub-components, the number of 'critical paths' which are best defined as chains of constraint which establish the final necessary constraint for a critical part. The fact that there are 2 in this case, informs the designer that both must be controlled and achieved for successful management of the final KC.

Figure 5-5: Analysis Results of DFC

Analysis	Value
Over Constrained	None
Under Constrained	Z, Tz
Number of Critical Paths	2

Analysis of Critical Path

A useful analysis involves the determination of 'critical pathways' which are responsible for establishing constraints necessary to ensure a critical attribute is met. For this simple example, the number and arrangement of critical pathways is related directly to those KC constraints that we consider critical. Looking again at the relationship between A and D, we may say that this relationship must be constrained along X, Y, and Z, and about Theta X and Theta Y. This leaves Theta Z free for the door to swing unconstrained. In this case, we are interested in assuring that all 5 constraints are provided for by tracing the pathways that provide these constraints. As seen in the table above, 1 of these (Theta Y) will remain unconstrained and each of the pathways will constrain 2 of the remaining degrees. For this case, both path ways (A-B-C-D as well as A-C-D) will be considered critical paths. However, we can imagine another case for which the only essential relationship is between car and hinge along the Z axis. This might grow out of a designer's concern about controlling the height of the car door with relation to the body and would lead to a single critical path: A-B-C-D, which is highlighted in green in Figure 5-6.

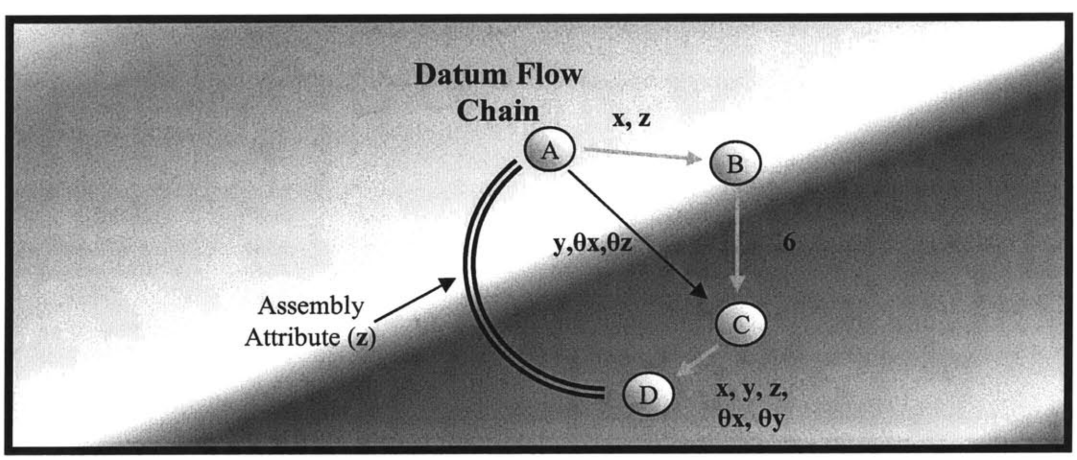


Figure 5-6: DFC Critical Path When the Critical Parameter is Along Z Only.

Once the critical path for a component or attribute has been identified, this information can be used to assess the ability of the design to meet requirements. The datum flow chain along a critical path shows the combination of assembled parts that are necessary to ensure quality, with each part playing a essential role as concerns its constraint state, geometry, location and tolerancing. As a design strategy for a given vehicle takes shape it must take into account these parameters – and by modifying one or more of these it becomes possible to improve the delivery of the KC. Once the critical paths have been identified, a variety of other mathematical tools (including design variation analysis and/or Monte Carlo analysis) can be employed to generate numeric validation of assembly-level attributes.

Analysis of KC Conflict

The identification of critical paths allows the designer to uncover potential attribute conflict in which two separate KCs share segments that pass between the same components. This situation makes it difficult to modify components to improve one KC without adversely affecting the other KCs. As a result, it is necessary to find a shared optimal point which allows all affected attributes to meet requirements. Such a point is not always easy or even possible to achieve, as the interactions between components and attributes may be non-linear and in other ways complex.

By way of example, consider again our simple system consisting of 4 components, the first hinge half (A), the second (B), the NAB pin (C), and the body surface (D). Imagine that we are intent on providing constraint between A and D in order to satisfy 2 KC's; one of which is satisfied by constraint along X and the other by constraint along Y. That is to say we want to be able to fix the door so that it cannot move left/right or in/out of the hinge. Analysis of critical paths shows us that both A-B-C-D (for the first KC) and A-C-D (for the second KC) are considered critical. Say then that improvement is needed concerning the ability to meet the second KC. Although it is reasonable to consider the redesign of component C (the NAB pin) in order to achieve this improvement, care must be taken that the redesign does not affect the part's ability to provide for the first KC by its X constraint achieved along the critical path A-B-C-D. In this way, part C can be thought of as having to satisfy two, potentially conflicting constraint requirements, both of which must be considered simultaneously. This part is said to be under the conditions of KC conflict.

Potentially more difficult situations of KC conflict occur when a part is expected to provide for the exact same dimensional constraint (e.g. along X) simultaneously for 2 separate KC's. For instance, a hinge may be expected to provide for the relationship in X of a door header to a car body while also being expected to control the relationship in X between a door handle and a car body. In each of these cases, it is first advisable to attempt to find components that do not suffer KC conflict and can be adjusted without affecting other unrelated KC conflict. As this is possible, solutions appropriate to a first order of complexity system apply. That is, those components can be freely adjusted to meet the related KC. However, in cases where adjustment of conflicted components is unavoidable, it is important that the entire affected system first be mapped out and understood using DFC techniques. This allows early identification of problems that may arise from such redesigns or other adjustments.

The Definition of Additional Design Metrics

A number of other measures of design robustness deserve a brief mention. The *longest critical path* length records the highest number of parts through which a critical path exists and may serve to indicate the tenuousness of the delivery of a given part or attribute. The longer the path, the greater the likelihood that a supporting part or linkage will not meet expectations. In general, a design with shorter critical paths is preferable to one with longer paths.

The liaison ratio refers to the number of liaisons to the number of parts within a given assembly. This fraction may be useful to Magna engineers over time as a means of comparing competing designs. Generally, it will serve to strive for lower values of this ratio (as assembly complexity will drop with fewer inter-part relationships), however as DFC's become available for several designs, it may help to establish more specific liaison target ranges for particular program subassemblies.

The *tooling ratio* refers to the number of different tools or fixtures used per number of assembled parts. This ratio may be of interest when assessing the additional work necessary for manufacturing engineers and operators, who must use such tooling to ensure a correct finished assembly. The larger the tooling ratio, the more effort will generally be required downstream by assembly and should therefore (in the absence of other factors) be minimized. Instead, designs that accomplish the necessary constraint through their particular geometry and modes of attachment are preferred.

The number of *interfacing organizations* summarizes which groups are responsible for the components or processes necessary for assembly. The greater this value is, the more cross-functional effort will be required to ensure the assembly comes together correctly. However, as this number increases, the potential for customer success is likely to increase due to the number of organizational stakeholders represented. As vehicle systems increase in complexity, the design engineer or CSI should work to develop designs that accommodate an increasing number of interfacing organizations, as input from each department becomes less trivial. However, from an organization perspective (possibly outside the purvue of our CSI), the divisional structure within Magna should be set to minimize the value of this metric. This is understood best by considering the benefits enjoyed by a division that has all necessary expertise within its own 'walls'. Practically, however, such an optimal organizational design is not achievable.

The number of in*dependently adjustable DOFs* is useful for determining which attribute constraints can be managed without affecting the entire system. For instance it may be useful to modify the relationship between two components along X, without changing how they relate to each other along Y or Z. In cases where vehicle assembly is expected to suffer from unacceptable variation (and to require periodic adjustment) this value should be maximized. Generally, as the independence of an assembly's degrees of freedom, the complexity of the system decreases. This is desireable provided that all customer requirements can still be satisfactorily designed for.

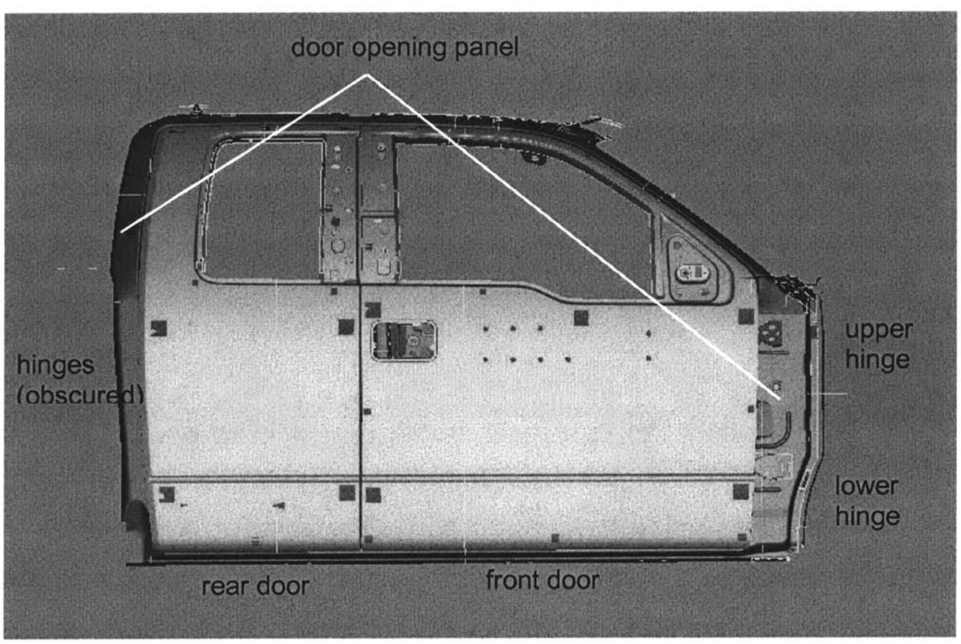
These metrics provide DFC users with advanced methods of design improvement that can be performed on virtually any system first mapped out using DFC techniques. In later chapters we will explore how these analyses give insight to good design at Magna and how they can be accomplished using the DFC Constructor Toolset. First though it is useful to apply DFC to the study of a door closure system for the Magna-duty truck line. However, in order to familiarize the reader with the manufacturing process used to assemble the truck's door system this next chapter will be devoted to a brief description of the current steps involved.

CHAPTER SIX: MANUFACTURING PROCESS FOR ASSEMBLY OF MAGNA-DUTY TRUCK DOOR HANG

A properly developed Datum Flow Chain should be careful to capture all the elements necessary for the correct assembly of a given system. Although much of the critical information can be gleaned from the existing CAD data and from documents supporting engineering design, the role of fixtures and tooling may be overlooked. Thus one approach for capturing the intended constraints and relationships is to begin at the end – by observing the final assembly of the vehicle. This chapter will seek to describe the build process in order to lay the groundwork for the construction of DFC's in the following chapters.

The assembly line is automated to advance by steps of predetermined length (equal to the length of the truck body) once each operator 'tags in' that he has completed his operation. Although most assembly steps are performed symmetrically on both the left and right hand of the vehicle, the following discussion will consider only the right side (i.e. from the perspective of the driver) as the truck advances. Ultimately, the assembly will result in a completed door closure system as shown in Figure 6-1.

Figure 6-1: Completed Door Closure System



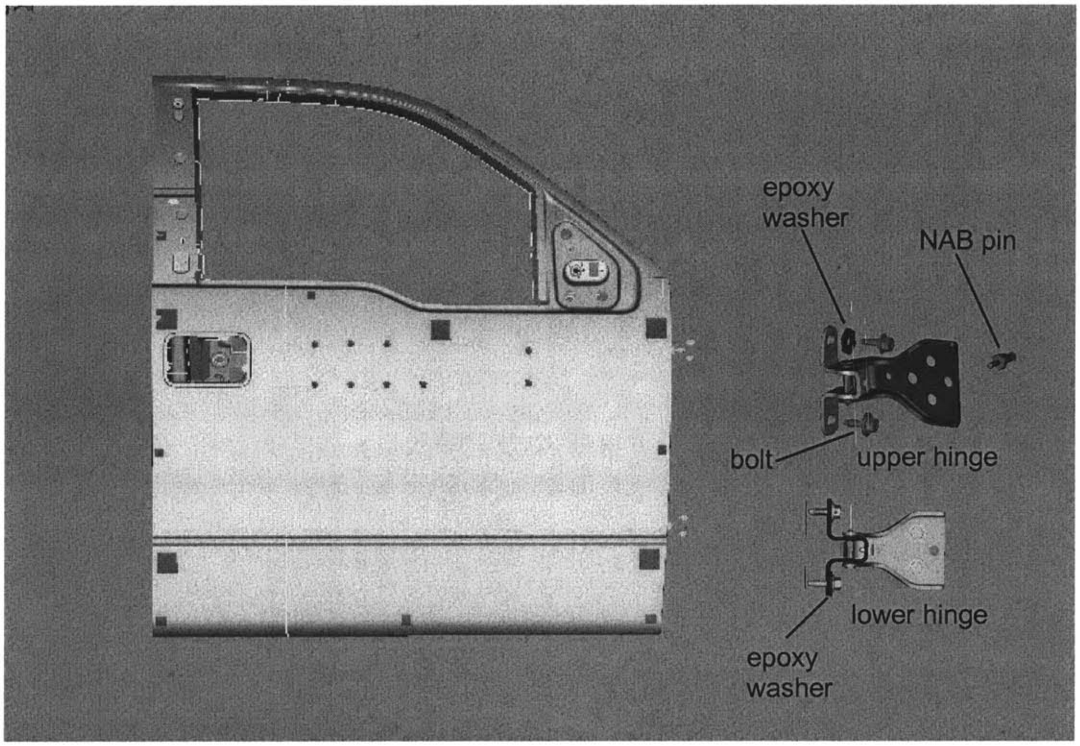
First Assembly Process: Hinge Set

The first process step which must be considered is the hanging of the rear door to the body of the truck. This is first accomplished by the use of a station which includes several fixtures such as the hinge set fixture (HSF) and the door hang fixture (DHF). First the operator manually loads a door onto a belt which brings it to the HSF. This door is held in place by the use of a 2-way and a 4-way locating hole along the inside of the inner door panel and then held in place by a series of clamps. Along with the door, the operator sets into place an upper and lower hinge which will be bolted to the door. Each hinge is located by the fixture using a 2-way / 4-way location scheme into two of the hinge holes, are then attached with 2 bolts (so 4 bolts total). This requires 4 guns to torque the bolts which align with the inner weld nuts which are situated on the door. A 5^{th} and 6^{th} gun are used to tighten down 2 NAB (no adjust build) pins, one for each hinge. The location of this NAB pin is also set by the HSF which serves as a proxy for the truck body.

Also one bolt for each hinge is paired with an epoxy washer before being loaded into its gun. This epoxy washer serves a critical role in alignment as the truck doors will later be removed from the body (without hinges) and installed a second time (this is known as 'doors-off' processing). The use of the washer, which is a tight fit with the bolt and which sticks firmly into place on the hinge, is to provide a feature for alignment for the hinge to door relationship. A washer is used for both hinges and is attached using the upper bolt for the upper hinge and the lower bolt for the lower hinge (see Figure 6-2 which shows this for the front door). Upon the door's rehang, the new bolt will align (on the hinge) with this washer and will also align (on the door) with the weld nut.

A similar process is employed for the truck's front door. However, in this scheme, only 1 NAB pin is used, and is bolted to the upper hinge. Figure 6-2 shows the attachment of both hinges (which are enlarged). The upper hinge is shown in its before-HSF state and the lower hinge is shown afterwards. In both cases, the hinge set fixture is responsible for setting the hinge's proper relation to the door, as well as for setting the correct position for the NAB pin which will serve to locate the door assembly to the body. The HSF mounts for hinges and door can be adjusted, as can their 2-way and 4-way locators, but only by relatively crude methods (i.e. wrenches and 'eye-balling' it). Adjustment is performed on an ad hoc basis, depending on how well the previous fits have come out.

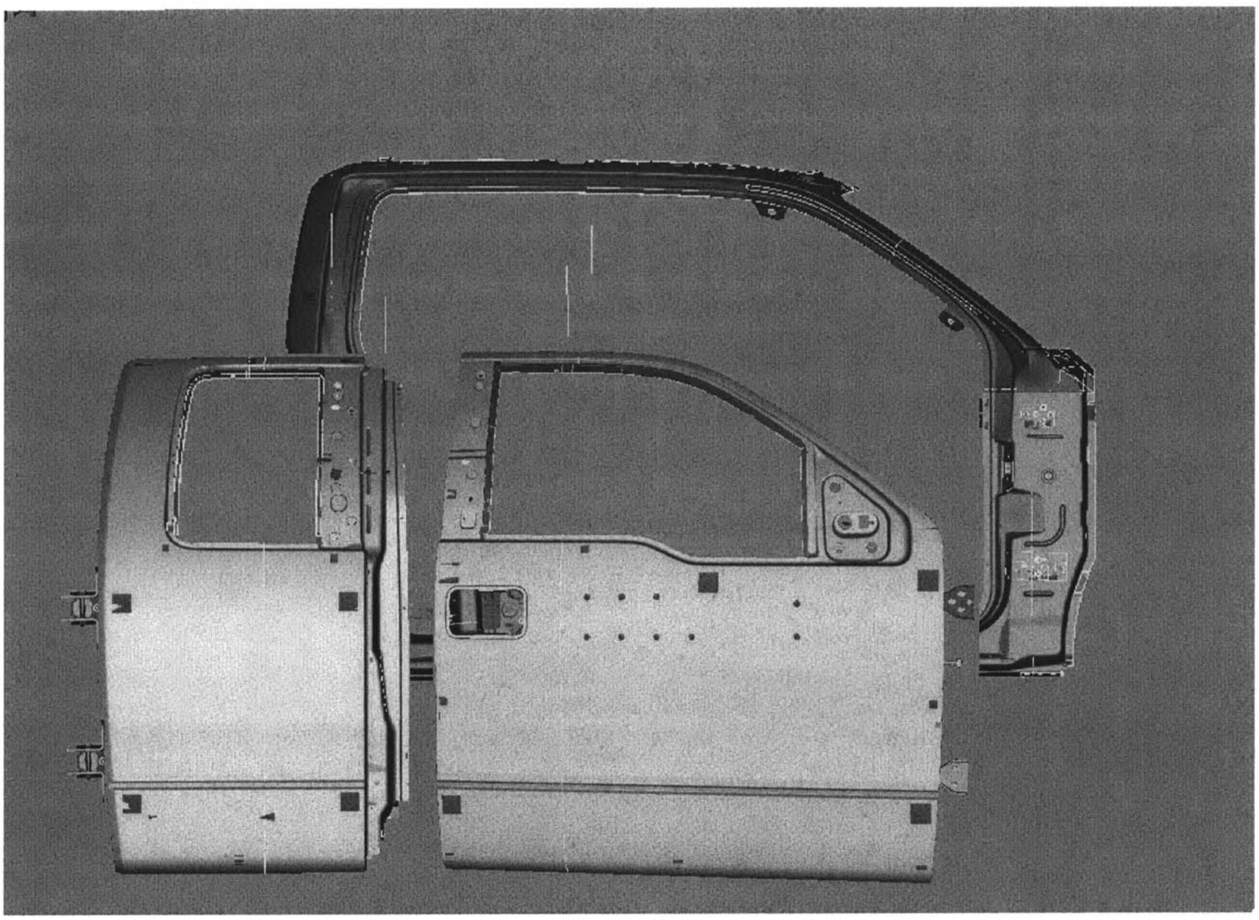
Figure 6-2: Front Door Hinges w/ NAB Pin and Washers



Second Assembly Process: Door Hang

Once the hinges have been properly secured to the rear door and front door, the doors are attached to the truck body at the door opening panel (DOP). They are lifted and placed into the frame by the use of a door hang fixture which provides a lift assist to the operator but does not serve to provide alignment for the door to body. This process is straightforward for the rear door as its two NAB pins align with two holes in the DOP (a 2-way and a 4-way) to ensure proper alignment. However, for the front door a special tool (the rocker tool) must be placed beforehand onto the lower flange of the body frame. This rocker tool is an S shaped piece that sits over the lower hem of the DOP and provides a surface for the front door to locate to during assembly. This is necessary for proper location since the door would otherwise rotate freely about its single NAB pin. Additionally, the rocker tool causes the door to be assembled with an up preset of ~2 mm (i.e. the door is jacked upwards by ~2mm) in preparation for the weight that will later be added by the addition of trim (an additional weight of more than 50 pounds). This offset is applied regardless of the specific vehicle styling – which determines the amount and weight of the trim to be added. At this point both hinges (or the upper hinge for the front door) have their NAB pins tightened which locates the door. The operator then tightens the remaining hinge bolts, locking the hinge (and thus the door) to the body.

Figure 6-3: Door Hang to Door Opening Panel



Third Assembly Process: Door Fit

The next series of operations to be performed takes place at door fit. Here, 2 fitters check the margin of each door and ensure that it meets a visual standard. The use of as-needed verification with calipers is encouraged but not required. Door systems found not to be within acceptable limits are adjusted. Adjustment is accomplished in a variety of ways including hammering the body at offending sections and hanging on an open door (to pull it downwards).

Fourth Assembly Process: Doors Removed and Reinstalled

Additional downstream processes should also be noted, including the removal of both doors from the vehicle after painting in order to facilitate final assembly. This is accomplished by removing the nuts which hold the hinges to the door. Later as the doors are reattached, the location of the epoxy washers ensures that the same alignment is captured and re-secured. This process requires the use of new nuts and bolts to provide this contact.

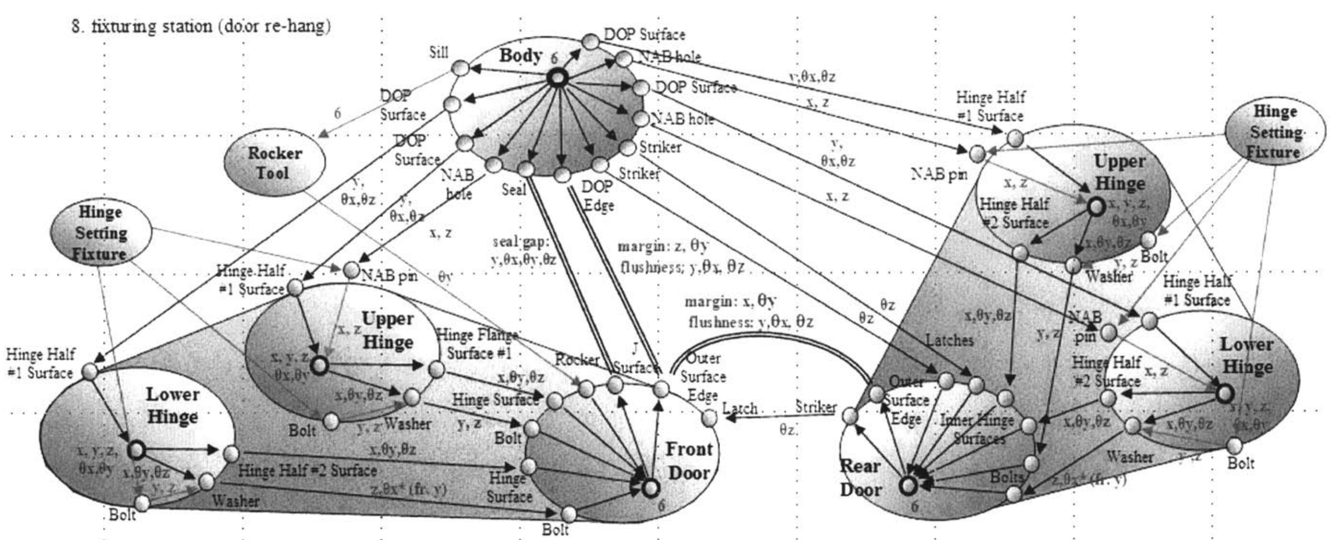
Other System Features Critical for the Success of the Door System

Not shown are the latches and strikers which engage to hold the door in place to the body. For the Magna-duty truck line this system relies on two strikers (metal bars) which are fastened to the DOP and which engage with latch mechanisms on the rear door. The rear door also contains a single striker which in turn engages with a single latch on the front door. This means that the rear door must be closed first (at which time its in/out position is set by these strikers), and then the front door must be closed into position.

CHAPTER SEVEN: DFC TECHNIQUES APPLIED TO MAGNA-DUTY TRUCK DOORS

Having laid the groundwork for the construction and use of Datum Flow Chains, we now turn our attention to their application to the previously described Magna-duty truck door hanging strategy. One of the advantages of the DFC approach is that it allows the user to start small, by analyzing subsystems, before combining the work to model the full system. For the purposes of this project, the use of the DFC toolset was sought as a means to improve wind noise associated with Magna-duty truck line. For that reason, the following steps describe its application to the front door seal gap which has previously been shown to correlate with wind noise. Ultimately, the DFC shown in Figure 7-1 was constructed and analyzed.

Figure 7-1: Complete Magna-duty DFC



Building up the DFC Subassemblies

In order to build up and analyze the total system DFC for the Magna-duty, it was necessary to begin with an understanding of the manufacturing processes by which the assembly was accomplished. Again, the primary four steps involved were:

1. Hinges are attached to the doors with automated Hinge Setting Fixture (HSF)
2. Doors are attached to truck body with semi-automated Door Hang Fixture

3. Doors and Body are 'fit' to ensure compliance
4. Doors are removed and later reinstalled

By observation of these steps it was possible to assign various constraints to part features and map their relationships, as will be seen below. Figures 7-2 and 7-3 recall the simplified version introduced earlier and involve a truck door fastened to a hinge which is in turn bolted to the truck's door opening panel. Here, the linkages are drawn over the operations sheet sketch, as is the critical characteristic for seal gap.

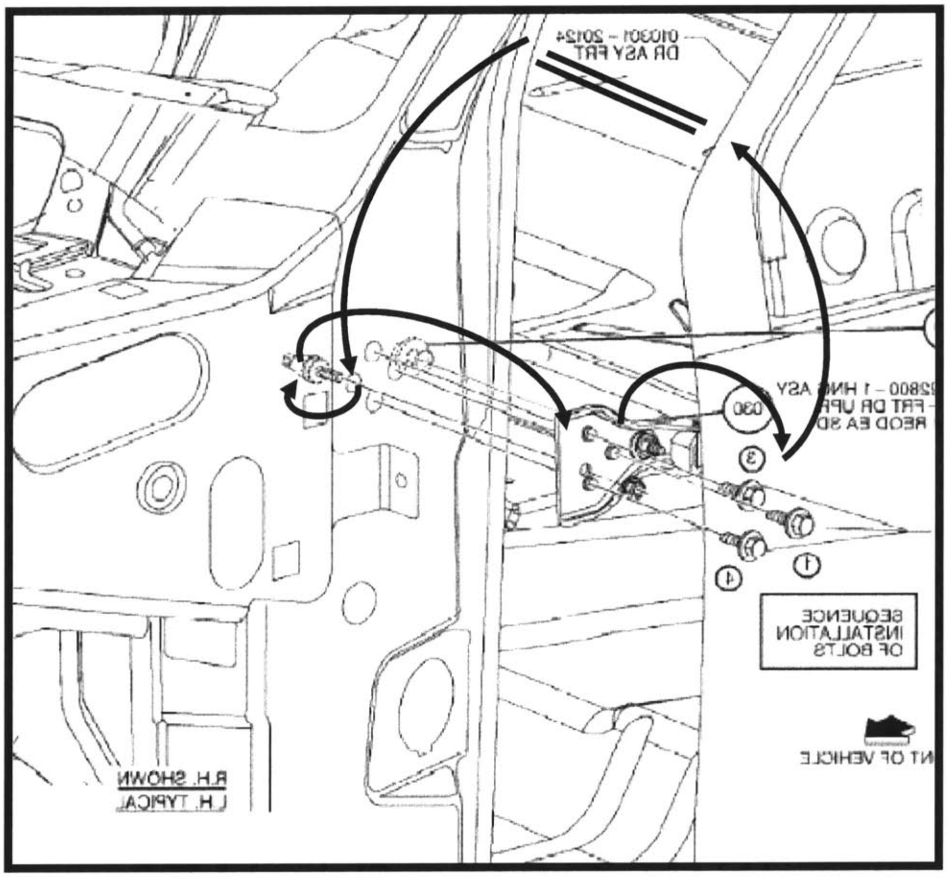


Figure 7-2: Door to Hinge to Body Relationship (image reversed)

Figure 7-3 serves as a staging point from which we can hope to identify the other contributing members of the assembly, and work through the constraints assigned to each.

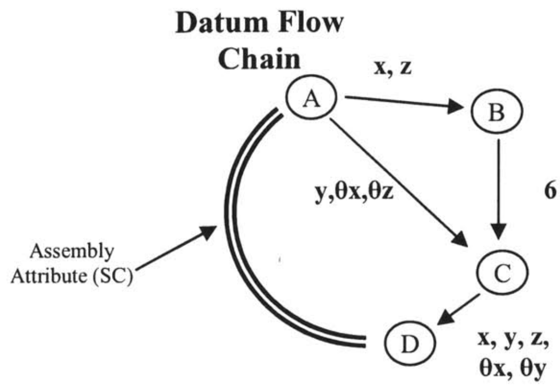


Figure 7-3: Simplified DFC

In order to build the entire door system DFC, we must continue to identify key subassemblies and then answer the question of how their relationship to each other is provided. A full DFC is capable of capturing each step of subassembly, all the way up from the most basic of components. However, in order to practically examine a process at a given point in time, it is useful to simplify the DFC by taking some level of prior assembly as given. As shown in Figure 7-4, the truck Body (which here we will treat as synonymous with the DOP) is assumed to be preassembled to contain the elements shown. A detailed discussion of every feature is not necessary as the relationship between essential features should make their purpose obvious. For the following DFC's, solid lines should be taken to indicate that all 6 constraints are being passed from node to node. Otherwise, particular constraints will be noted. Subcomponents and features are represented by the smaller nodes.

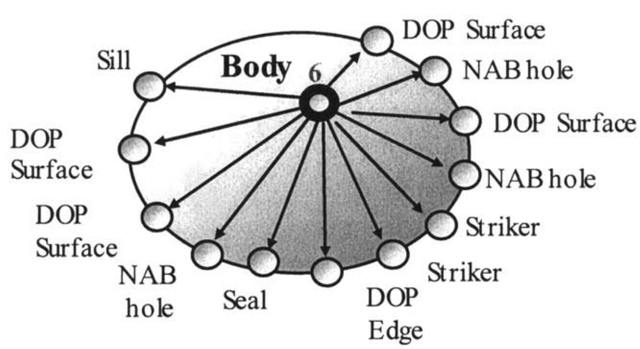


Figure 7-4: Truck Body DFC

In the same way, the figure below depicts the state of both front door hinges prior to the hinge set fixture. Notice that there exists only 1 NAB pin which is not yet constrained to the rest of the hinge. This is due to the loose state of the pin prior to fastening within the HSF. However, constraint has already been established internal to the hinge (through its pin) by its prior assembly.

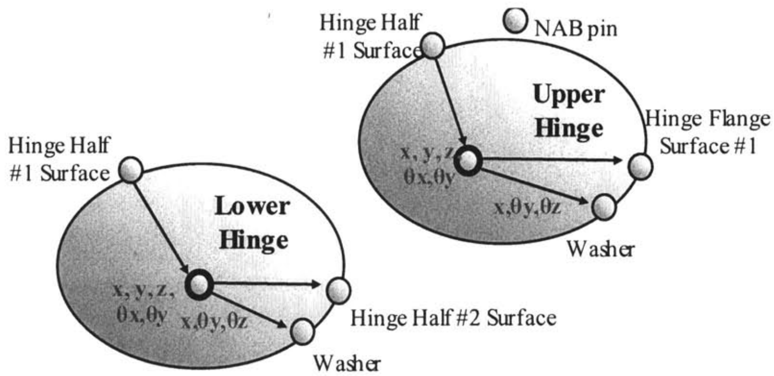


Figure 7-5: Truck Hinge DFC

Figure 7-6 shows the simplified DFC for the truck's front door, which at this point is known to consist of an inner door panel, and outer door panel and as well as bolts threaded through weld nuts, and a latch which is allowed to float.

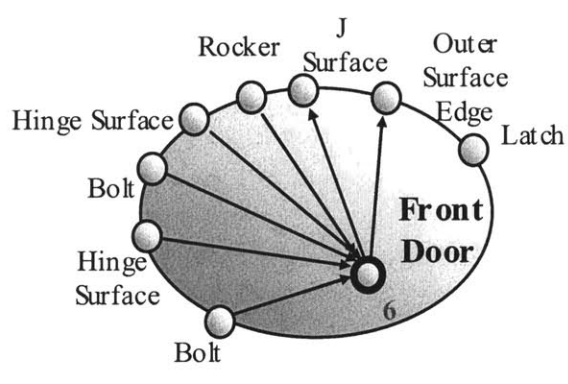


Figure 7-6: Truck Front Door DFC

Using these simple building blocks, it is possible to build up the DFC shown in Figure 7-7, which is called the Front Door-to-Body DFC. This DFC involves only four principal nodes (the door, the body, and two hinges). Features found on the truck body (such as the DOP surface and the NAB hole) are considered rigid and fixed to the body and are left with no degrees of freedom. By contrast, the central node within each hinge shows that Theta Z (rotation about the vertical) is not constrained and so that degree of freedom remains open. Similarly, Theta Y is not provided to the door from the body.

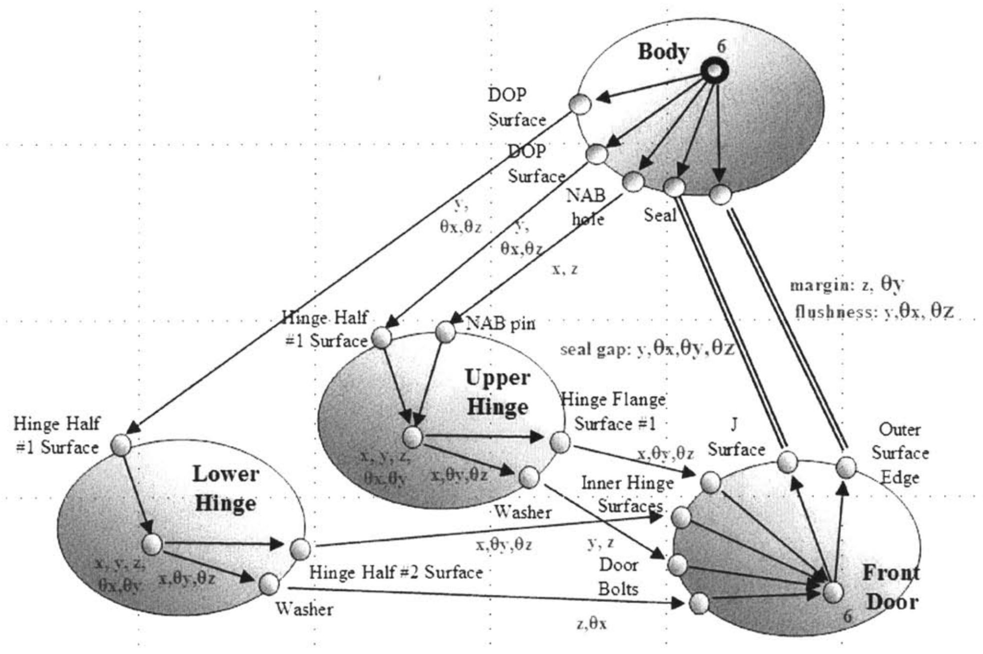


Figure 7-7: Front Door-to-Body DFC

The key characteristics (shown as double lines) represent the critical margin and flushness between the upper portion of the door header and the corresponding portion of the truck body. Although this diagram represents a semi-complete front door system it was constructed without consideration of the process or the tooling required to locate and constrain each component. For instance, this DFC shows the upper hinge's NAB pin now locked (along all 6 degrees of freedom) to the hinge, whereas previously it was left to float.

Before turning our attention the use of fixtures, we will first complete this DFC model for the entire door closure system. Figure 7-8 shows the addition of the Magna-duty rear door, which is similar in kind to the front door, but with the use of 2 NAB pins.

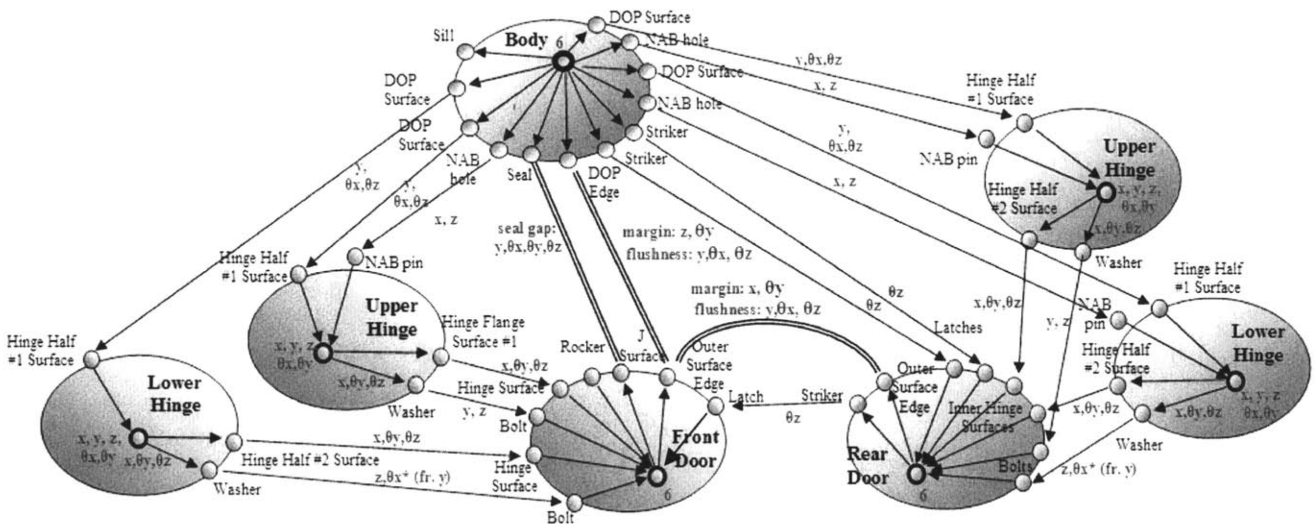


Figure 7-8: Front and Rear Door-to-Body DFC

With the addition of the rear door, rotation about Z is constrained. This is done by the engagement of the front door latch mechanism with the striker of the rear door. The rear door receives its constraint about Z also through a striker and latch mechanism via the truck body.

Identification of Constraint

Although this DFC can be considered complete from a component perspective, it still lacks the identification of fixtures and tooling which provide additional constraints. It also gives only a partial explanation of those relationships shown. For instance, how did our NAB pin become locked to the front door's upper hinge (in Figure 7-8), when previously it was left to float (Figure 7-6). The intervening steps involved the use of fixtures which have yet to be represented. One necessary fixture – still to be introduced – is that of the rocker tool, without which any DFC analysis of Figure 7-8 would be incomplete, and would generate an under-constrained condition. Full consideration of constraints must always be performed after addition of components, subassemblies, and fixtures. Figure 7-9 shows the use of the HSF and rocker tool to provide the necessary constraints for the system. For our purposes fixtures or tools and the constraints they provide are shown in red. As discussed previously, a rocker tool is only necessary for the assembly of the front door to body, as the rear door makes use of a 2 NAB pin design to achieve constraint in Theta Y. The HSF is needed for both doors to provide various inter-part constraints which – once set – are fixed in place for future states. In fact, it is this advantage of Datum Flow Chain analysis: its ability to consider systems before, during or after the use of fixtures and tooling that make it such a flexible tool for informing design.

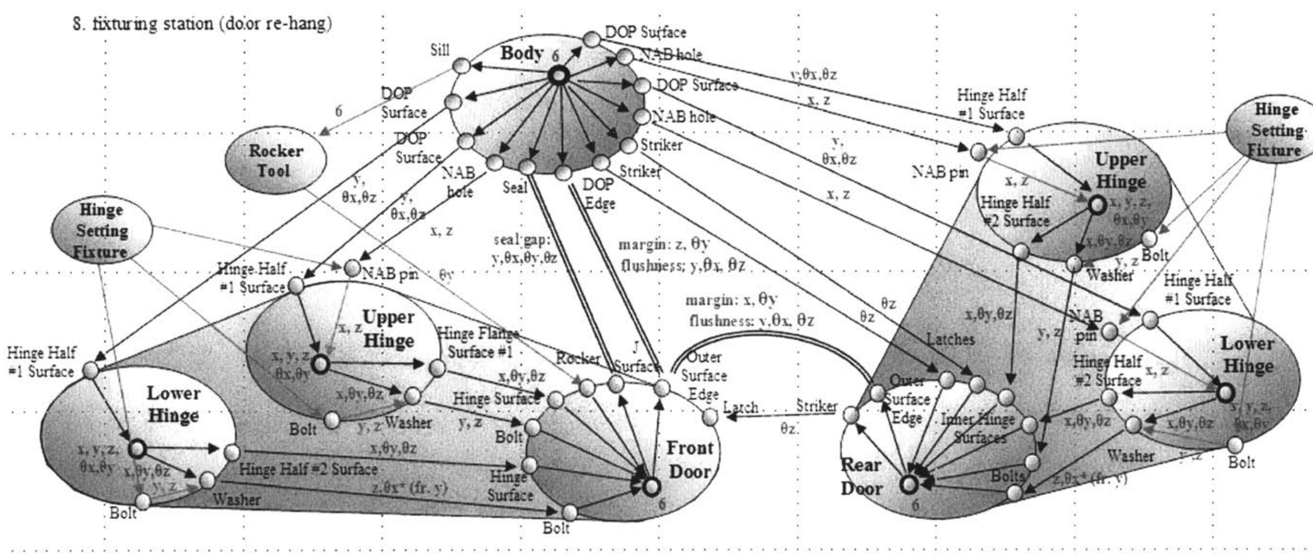


Figure 7-9: Completed Door System DFC

Time Considerations of DFC Analysis

One element of the DFC that makes it particularly powerful, but also at times confusing, is its ability to model an assembly at any point in time – such as before or after the use fixtures to lock components to one another. Because of this DFC's should generally be constructed to reflect a particular time frame in order to prove most useful to informing design. The figure above is an attempt to represent the coordination of all locating fixtures needed in the subassembly, in order to provide a single graphic capturing the entire 'story' of system design. However, for analysis purposes, as we will see below, a DFC user must be careful to clearly identify the time frame of his design. Alternatively, as analysis is developed to better understand a collection of KC's it may be necessary to consider multiple time frames in order.

CHAPTER EIGHT: ANALYSIS AND RECOMMENDATIONS STEMMING FROM MAGNA-LINE DFC

Having constructed the full Datum Flow Chain representing the relationships between door system components, we now begin a fundamental analysis to determine the critical paths and potential conflicts resulting from the current design. We will then consider the use of other methods for achieving the same key characteristics.

Identification of Critical Path

Figure 8-1 provides the identification of the critical path necessary to assure that the front door to body margin is properly constrained. The path in green shows the route taken to provide for both of the critical constraints (Z and Theta Y) in order to achieve the defined margin. As a result, each of the components along the chain must all be considered critical to delivery of this characteristic.

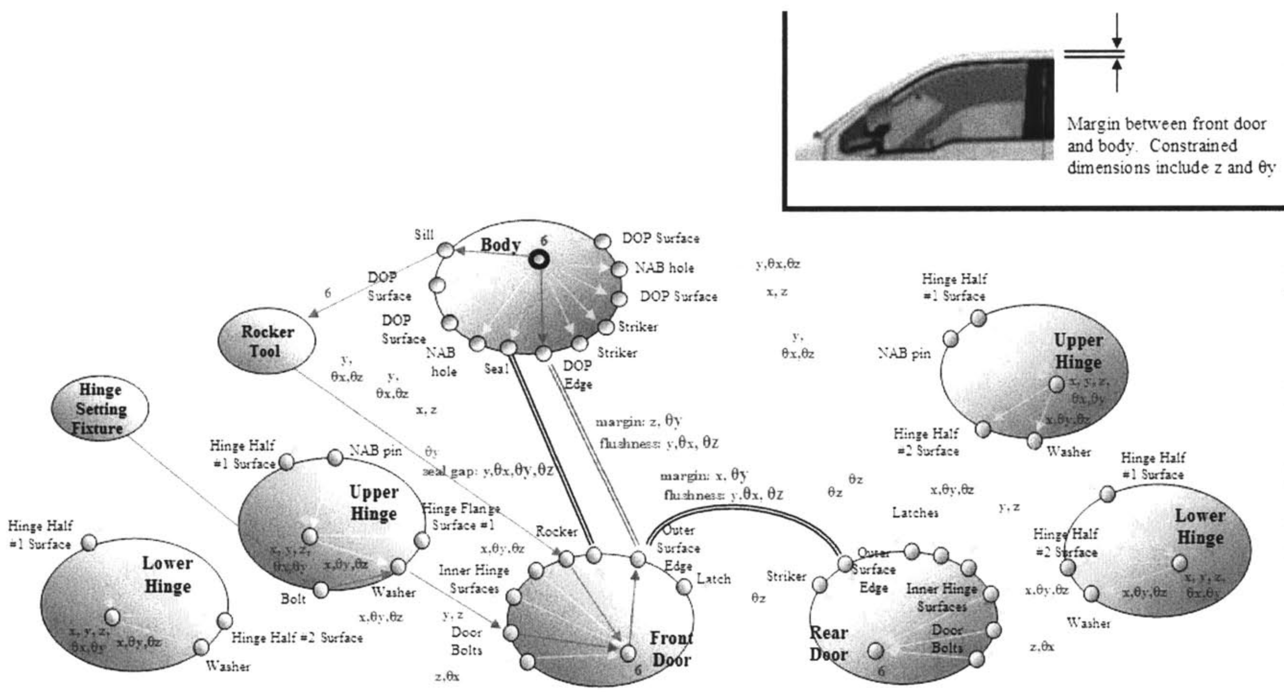


Figure 8-1: Critical Path for Door Margin

Once the critical path has been identified across the entire system, it is a simple matter to trim away the less critical components to focus on the particulars of those necessary for establishing constraint. Figure 8-2 shows this clarified DFC. The primary role played by tooling should be evident. Although the upper hinge is considered a part of the critical chain – and is partially responsible for providing for the location of the door along Z – it is dependent on the HSF to set the location of the washer by the use of the fixture's bolt. Note also the use of the rocker tool to establish constraint for the door's rotation about Y.

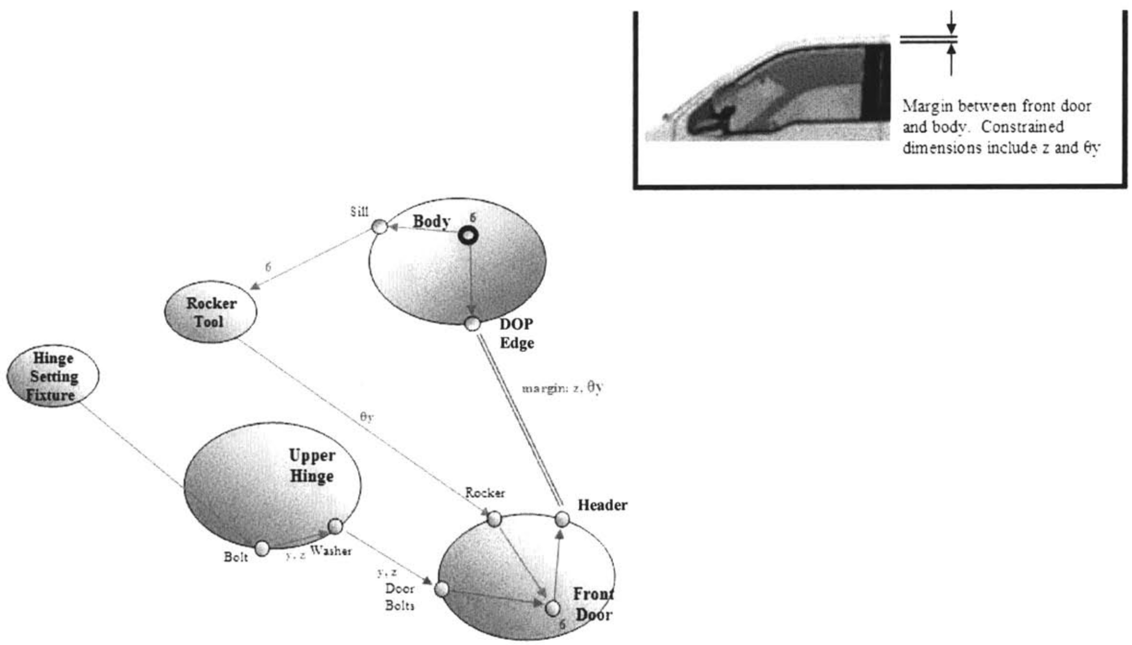


Figure 8-2: Simplified DFC Showing Critical Path

By following the critical chain from part to part it is possible to focus on the specific components that require further analysis. Our vehicle margin has been defined to require constraint along Z and about Y as provided by this chain, and so only the establishment of these constraints is considered here. In this case the vehicle body is considered fixed to the sill which provides all 6 constraints to the rocker tool. This rocker tool then provides the necessary Theta Y to the rocker of the door, and thus ultimately to the header, establishing 1 of the 2 necessary constraints. The Z constraint is passed by the use of the HSF which aligns the upper hinge to the front door and fixes this relationship fast through the installation of a bolt and washer. This washer will prove critical for later realignment of this door (not discussed here) and will provide constraint through its exact fit with bolts – which in turn mate with the front door.

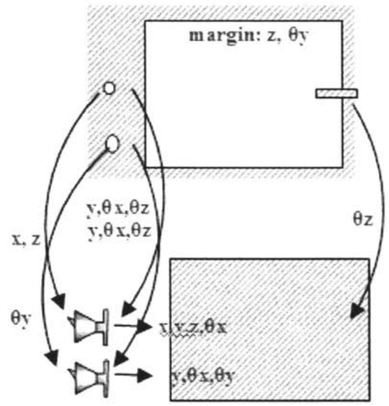
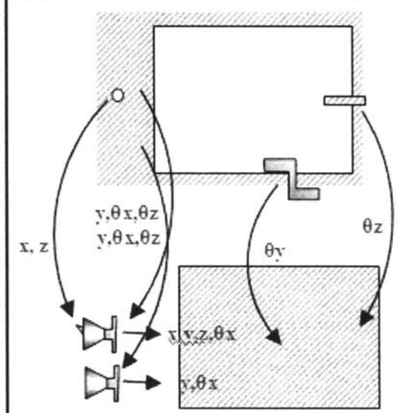
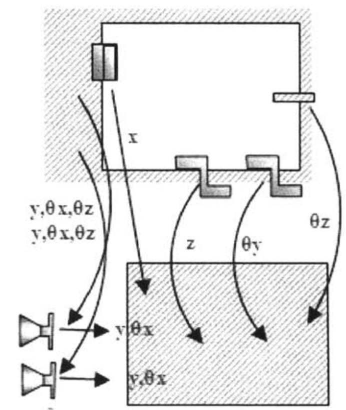
This part-by-part analysis can be particularly useful when paired with the techniques available through DVA. By first determining the critical chain and then exploring the response to introduced variation, qualitative design improvements can be discovered. The chain of components thus becomes a tolerance chain which can be subjected to DVA techniques. However, even in the absence of Monte Carlo simulation, basic comparisons of assembly strategies can prove useful.

Comparison of Design Strategies

One advantage of having considered a program's design using the DFC methodology is the ease at which design strategies can be developed and evaluated. As will be shown in Figure 8-3, there are multiple ways to accomplish a critical chain between components such as a door and a truck body – and multiple hinge designs which can accomplish this. For instance, the current design involves the front door being hung with the use of a single NAB pin and a rocker tool, whereas the rear door is hung with two NAB pins and no rocker tool. The choice of each of these was founded on the constraints which the designer needed to provide to the door from the body, and by the effectiveness of these particular designs to achieve KC's such as margin, flushness and seal gap. Other choices were certainly available. For instance the designer could have elected to use two hinges, each with a NAB pin for the front door, or else to have hung either door using hinges with no NAB pins. The consequences of each of the decisions are considered in Figure 8-3 and contrasted with one another.

The final design consequences in the table below proves particularly important to the design considerations due to the difference in mass associated with each of the two truck doors. Once fully outfitted with all the package trim, the Magna-truck front door is typically 3 to 4 times heavier than the rear door. The massiveness of this door makes it difficult to control KC's if the locators passing constraint are far removed from area of interest. Because of this, the strategy preferred for the front door was the second one – a single NAB pin and a rocker tool in order to provide constraint in a way that is closer to the door header where a number of Key Characteristics have a tendency to demonstrate reduced performance.

Figure 8-3: Comparison of Hang Strategies

	2 NAB Pin Hang Strategy	**1 NAB Pin Hang Strategy**	**No NAB Pin Hang Strategy**
			
Over/Under Constrained	Over: y, Tx Under: None	Over: y, Tx Under: None	Over: y, Tx Under: None
Parts contributing to above door margin	NAB hole – NAB pin – Hinge – Door	NAB hole-NAB pin-Hinge-Door DOP sill-rocker tool-Door	DOP sill-rocker tool-Door
Tooling/ Fixtures	Fixture1: Secure NAB pin to hinge (x,z, Ty) Fixture2: Secure hinge to door (y)	Fixture1: Secure NAB pin to hinge (x,z) Fixture2: Secure hinge to door (y) Tool1: Rocker tool (Ty)	Fixture1: Secure hinge to door (y) Tool1,2: Rocker Tools (z, Ty) Tool3: Flange Tool (x)
Number of Processes	punch hole, assemble DOP, Hinge to Door, NAB pin to Hinge, Door to DOP	Punch hole, assemble DOP, Hinge to Door, NAB pin to Hinge, Rocker Tool, Door to DOP	Punch hole, assemble DOP, Hinge to Door, NAB pin to Hinge, Rocker Tools, Door to DOP
DOF Independence for Door/Body	Tz	Ty, Tz	x, z, Ty, Tz
Difficulty to Adjust	X: medium (2 fixture adjusts) Y: hard (net fixture adjust) Z: easy (1 fixture adjust) Tx: very hard (from DOP) Ty: easy (1 fixture adjust) Tz: easy/med (1 part adjust)	X: medium (2 fixture adjusts) Y: hard (net fixture adjust) Z: easy (1 fixture adjust) Tx: very hard (from DOP) Ty: easy (1 tool adjust) Tz: easy/med (1 part adjust)	X: easy (1 tool adjust) Y: hard (net fixture adjust) Z: easy (1 tool adjust) Tx: very hard (from DOP) Ty: easy (1 tool adjust) Tz: easy/med (1 part adjust)
Distance from locator to KC	**high**	**low**	**low**

Identification of Organizational Responsibility

Having developed the basic DFC for a system, it is also possible to apply qualitative analyses as a means of discovering potential improvements. One qualitative method for doing this is to identify the functions responsible for ensuring that the dimensions of critical parts are achieved. The DFC is useful for this functional assignment of responsibility because once the critical components have been identified; it is possible to match the design of them back to particular groups or even individuals. Similarly, it is possible to match the responsibility of subsystem manufacturing to certain groups, as shown in Figure 8-4. Here the groups responsible for component fabrication are shown in green outline. Magna currently outsources the production of its hinges to a vendor who produces castings. Similarly, Body and Stamping can be thought of as internal suppliers who fabricate and assemble subcomponents which are delivered to Final Assembly. It is important to reiterate the interdependence of all system attributes, and the need to not use functional assignments as a means of assessing blame. The responsibility of each department must not be used merely as an excuse for not meeting certain requirements. Instead, the development of diagrams such as that shown below should be used to encourage greater communication between mutually responsible groups and individuals, and aid in the resolving of complex systems issues.

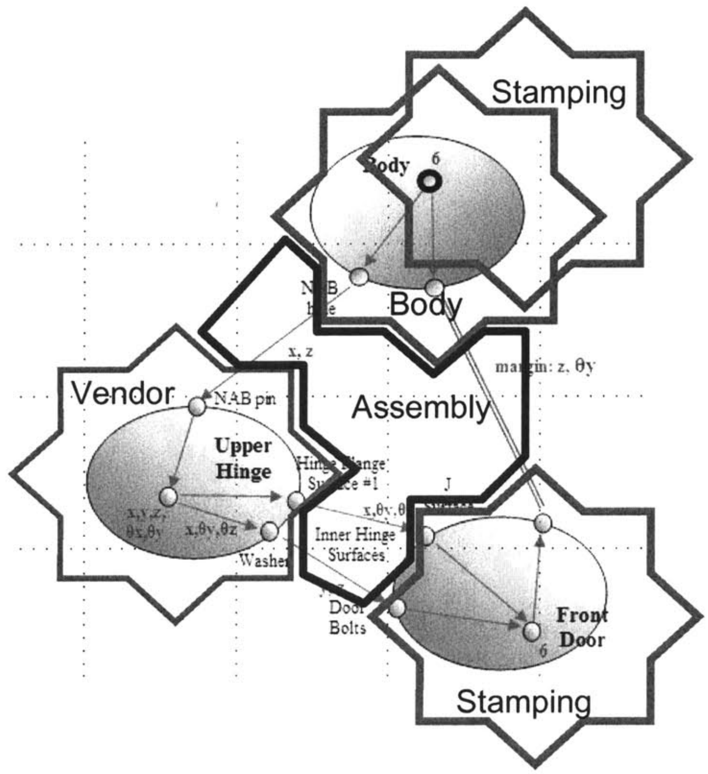


Figure 8-4: Organizational Mapping of the DFC

Combining DFC and DVA Techniques

Datum Flow Chains provide a powerful method of allocating constraints and component responsibility across an engineered system. However, it is not necessary to rely solely on DFC techniques when attempting to understand and improve a given system. Instead, the techniques provided by Dimensional Variation Analysis offer a established set of analytical methods by which the relationships discovered using DFC can be studied. When used in concert, these two collections of tools can build off of one another and allow the development of solutions that avail themselves of the visual elements and process mapping associated with DFC, as well as the Monte Carlo analysis and real CAD data of DVA. Ultimately it is desirable to have the two methods take greater root across the organization and find a home with the design engineers and CSI's responsible for improving customer satisfaction. The next chapter will consider how the DFC techniques presented above can be more fully integrated into the DVA techniques already used within the organization.

CHAPTER NINE: Incorporating the use of DFC Techniques at Magna

The Implementation of DFC within the Organization

As Magna works to develop a greater understanding of its own systems, and to apply standards which decrease complexity while enabling the flow of critical customer information back up the design chain faster, it is useful to consider the role that DFC might play. The timing of its recommended use within the organization should be early in the design period, before final closure strategies (or others) have been set. Although it is unlikely that the DFC toolset would be used before or during the work of the design studio (who develop body styling and the 'look and feel' of the vehicle), it should find a natural home within the group of Product Development Closure System Integrators. These engineers typically represent the group most responsible for meeting or improving on customer requirements and their lack of systematic tools has already been highlighted. Not only would DFC aid the PD CSI's in their consideration of the entire system for design purposes, it would serve to represent the relationships between shared components that are critical to satisfying the various CSIs' KC's and encourage dialogue about how these components can be modified in ways that are mutually beneficial.

Specifically, the use envisioned for the DFC toolset is as follows. As PD CSI's are presented with initial vehicle designs and begin their collaboration with Core Engineering on which strategies are most viable, they would construct simple DFC's contrasting the salient features of each design. Some design flaws and subsequent improvements may present themselves immediately and so lead to iterations and superior designs. However, even in cases where the exercise of constructing and discussing a DFC does not lead to ostensible product improvement, it will serve as a means to document the agreed upon design strategy and should ease the communication of these decisions to groups that are related or affected. Moreover, these documented DFCs will serve as guides in the event that the design needs to be rethought or refined. Over time, it is desirable that a library of these DFC's be built up and serve as an archive of design decisions made across a wide array of programs. As these DFC's are completed, approved and archived, they will be considered to be the DFC standards for future design work. The establishment of these standards should not prevent the development of new system designs through the creation of new DFC's, but will rather provide benchmarks against which future strategies can be measured.

Although a constructed DFC may appear to be a static creation, in reality it is not. It is continuously adjustable and can morph and evolve with the design it models. These DFC's are not merely useful to encourage cross-functional communication among groups, but can be leveraged as a means of recording the reasoning behind design decisions, and as a vehicle for passing this information on to future generations of programs. DFC then can serve in the capacity of relaying lessons learned and allowing each set of CSI's a unique means of communicating with one another.

Coordinating the use of DFC and DVA

As mentioned, the combination of DFC and DVA techniques would give Magna a solid method of system design and analysis. It is recommended that as DFC becomes increasingly established within the organization, that it serve as a first analysis of any given design – as it provides the impetus for collecting the necessary inputs from related groups and generating necessary discussion and brainstorming. Once the DFC model has been considered, basic constraints established, and some elementary analysis performed, it will be necessary to decide on the geometry to be associated with the critically constraining features of each subcomponent. This information can then be passed to VisVSA (or other DVA or simple Monte Carlo software) to analyze the ability of the agreed geometry to meet the expected KC values. Specifically, as DFC identifies critical paths that must be achieved and then suggests improved designs capable of meeting requirements, DVA should then be capable of performing the analysis necessary to confirm that the given flow of constraints will be accomplishable. This analysis involves the association of tolerances (either stemming from the component's design or fabrication), to each part and solving for the total error that may be introduced into the system. Some iteration of these two steps is expected, but with the majority of time and effort being dedicated up-front to the construction of the DFC.

It is further recommended that the responsibility for the incorporation of both DFC and DVA fall jointly to the team of PD CSI's who are expected to meet the KCs of a particular system. Although it these PD CSI's may bear ultimate responsibility for the design work necessary to optimize a given closure system, they must rely heavily on the input coming from engineers intimately familiar with the each particular component's design and fabrication. Although their working relationship with the designers has already been well-established, their need for regular, in-depth meetings with representatives from manufacturing has recently been acknowledged and improved through the use of the manufacturing CSI's. These CSI's are critical to informing the PD CSI's' designs by relaying the manufacturing capabilities and variation associated with the plant operations. This should not be seen as an 'over-the-wall' knowledge transfer from mfg CSI's to PD CSI's. Rather, the mfg CSI's should be considered partners that are able to help generate increasingly robust designs early with the design process. As the upstream information flow is improved through the partnership of each group of CSI's, Magna hopes to witness a corresponding improvement in the management of complexity as it affects their programs' closure systems.

Potential DFC Organizational Issues

In order for the implementation and use of DFC to become a reality, a number of organizational barriers may need to be overcome. These include many of the difficulties already considered for the use of DVA. Additionally, the following may be true:

- The PD CSI's already find themselves too busy to invest in a new tool. This dynamic can prove particularly pernicious to escape from, since the use of DFC with DVA ultimately assures the improvement of program designs and less need for rework of inadequate designs.
- The PD CSI's may have limited interest in the use of a toolset they consider to difficult or too lengthy to implement. For those not already familiar with DFC approach and thinking, the adoption of the system can at first appear overwhelming.
- There is a potential lack of standardization in DFC construction methods used by different PD CSI's. This concern stems from the lack of common standards governing the creation and analysis of Datum Flow Chains. Although the toolset does provide a

common language and a general approach that can be followed by all, the particulars of its use may vary slightly by user. This has the potential to greatly increase the difficulty a PD CSI faces as he attempts to read and understand DFC's that have been archived in the library.

Management Recommendations for Overcoming Resistance

In order for the DFC use to become commonplace within the organization (or at least among PD CSI's), it is critical that Magna management appreciate the effort necessary to roll this initiative out. The involvement of management entails the development of appropriate incentives for the use of DFC or DVA tools by PD CSI's. It also should include helping these engineers to de-prioritize current tasks (given their heavy workload) in order to leave time for becoming expert in the use of these tools. Finally, management must lead by example and demonstrate their commitment to supporting Magna's push to develop improved system's thinking.

The Use of DFC Constructor Toolset Software

The three sources of resistance: lack of time to use DFC, complexity of DFC, and lack of standardization of DFC can also be addressed through a technical solution. The development of DFC software – using an intuitive visual interface – should allow the PD CSI's to perform DFC analysis in less time, with less effort, and according to the protocols established by the software. For this reason, the final result of the internship project was the completion of the DFC Constructor Toolset which will be described in the next chapter.

CHAPTER TEN: CREATION AND USE OF DFC CONSTRUCTION TOOLSET

Introduction and Explanation of Platform

In order to create a more user-friendly method for introducing Magna engineers to DFC techniques, the DFC Construction Toolset (DFCCT) was created. This toolset runs as a collection of stencils and macros atop the standard Microsoft Visio software product and can be made available to virtually every PC user at Magna. Visio permits a standardized work environment by providing a common set of stencils which are used in the construction of visual objects. A collection of stencils were developed to cover the graphical elements essential for a DFC. The DFC stencil contains the following elements, which will be explained in an example below: Base Node (BsNode), Small Node (SmNode), Large Node (LgNode), Fixture Node (FxNode), Linkage, Fixture Linkage, Key Characteristic (KC).

The visual interface presents the user with four key areas of interest are labeled below and include:

- The Stencil: Where the user can select from nodes, linkages, and KCs for use as building blocks of the DFC
- The DFC User Toolbar: Where the user can select methods of DFC analysis
- The Properties Box: Which displays constraints and labels for each DFC element
- The Workspace: Where the user constructs and controls the DFC

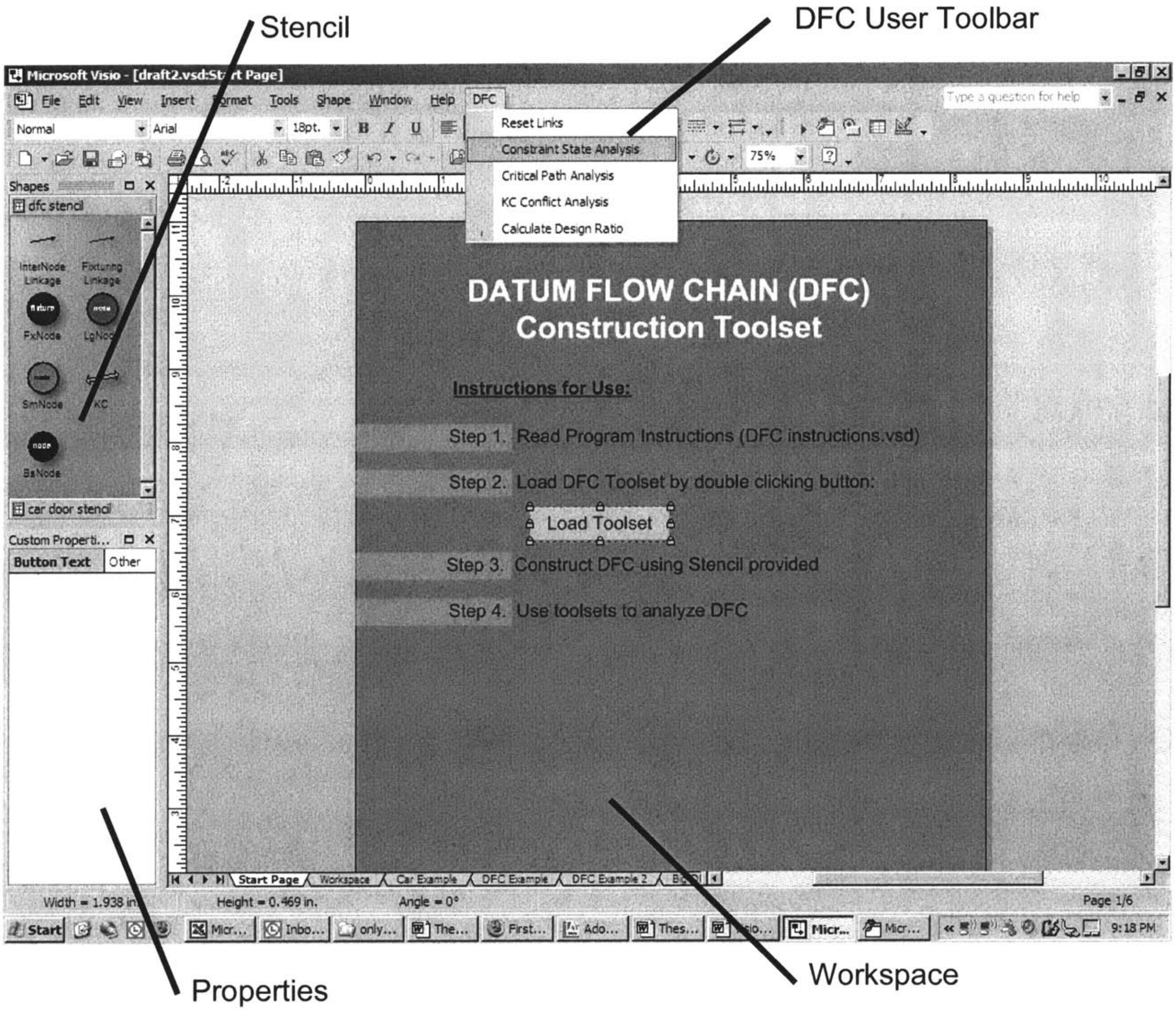


Figure 10-1: DFCCT Introductory Screen

Value of Automation / Software

For the construction of simple DFC's, a manually constructed 'pen-and-paper' model is reasonable. However, as was noted in previous chapters, the visual complexity and analytical intricacy increase dramatically as the system grows above a very few components. The use of a software interface allows the construction and analysis of a more involved system and prevents basic mathematical errors on the part of the user. Furthermore, by utilizing a standard interface, a DFC can be developed and used by more than one individual. Such an interface ensures a common method of construction and analysis and provides a common language to be used across organizations.

Initial Use and Familiarization

The initial use of and user familiarization is aided by a stencil which can be selected for the placement of visually familiar vehicle components. Although models built using this stencil are not available for analysis, they allow the user the opportunity to test the user environment separately from learning and adopting the proper DFC techniques. Figure 30 shows this introductory use of the DFC Construction Toolset.

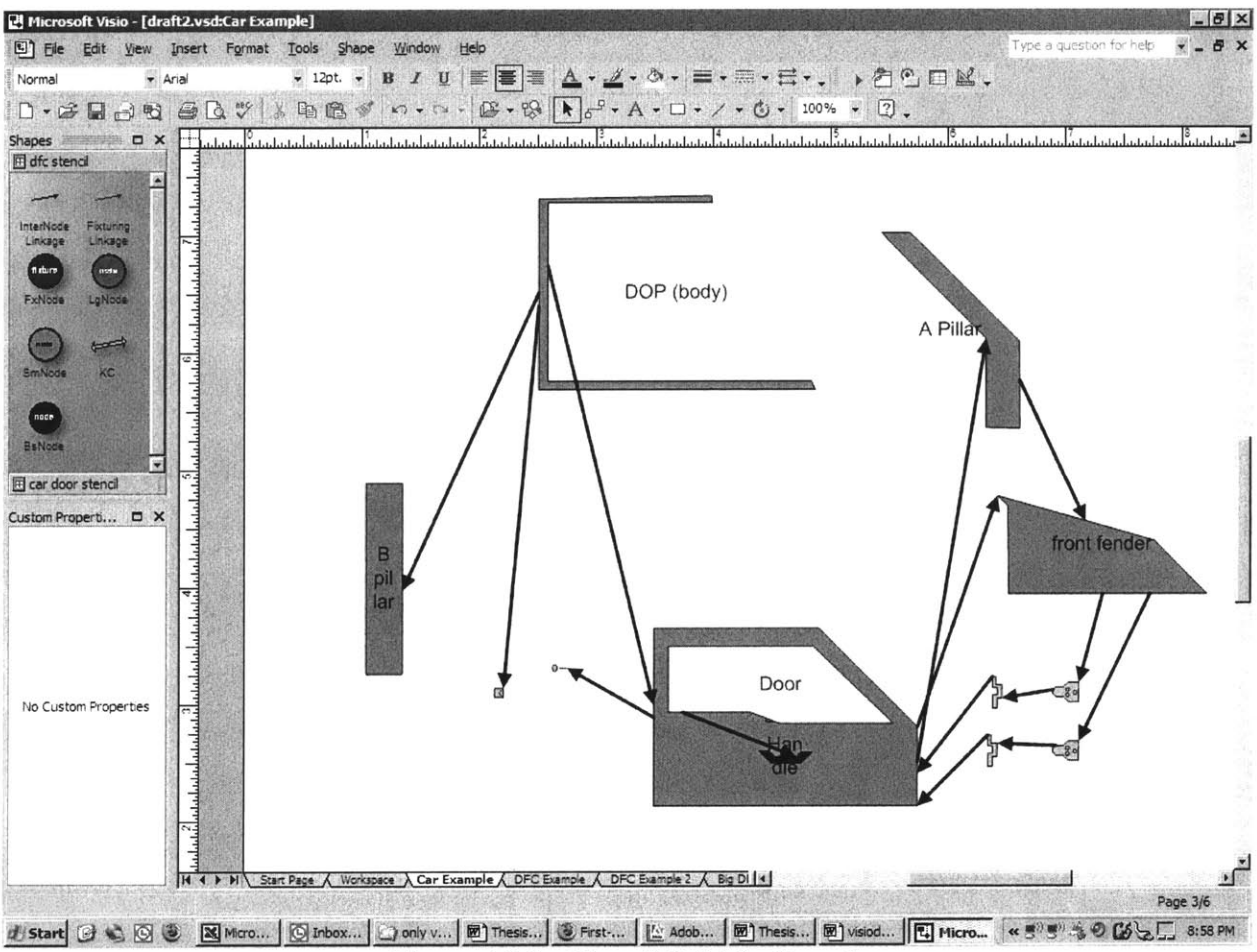


Figure 10-2: Use of Vehicle Stencil

DFCCT: Simple Example

The example shown in Figure 10-3 demonstrates a fully constructed DFC. Names and constraints for each node, linkage, and KC are displayed in the Properties box as the element is clicked. In this way it is possible to fully identify every aspect of the DFC. For ease of visibility, and advanced analysis, multiple versions of nodes can be selected and used for construction. These include base nodes (to set as the origin of the DFC), large and small nodes (for identification) and fixture nodes (to represent the constraints supplied by tooling or fixtures). Similarly, linkages are selectable both for constraints passed by components as well as constraints passed by fixtures.

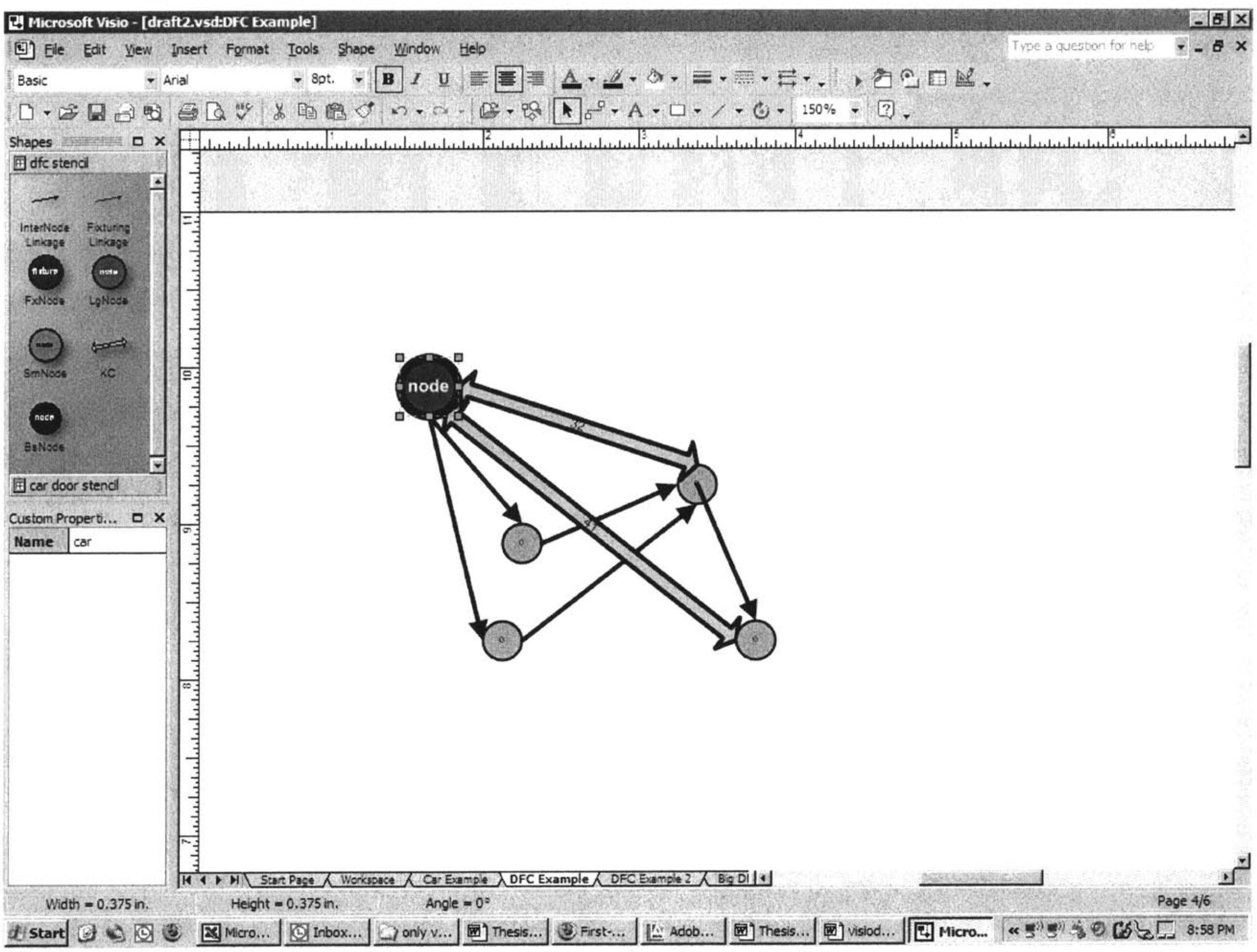


Figure 10-3: Simple Example

Constructing DFC

As each element is dragged into the workspace, the user will be prompted for parameters necessary for completing the DFC. This may include the name of an element and the number and type of DOFs being constrained. These parameters are intended to be entered as each element is created, but can be postponed according to the user's wishes. In order to view an element's parameters, the user must select the element and note the information displayed in the Properties box. As each linkage is placed, the user is responsible for connecting either end to the parts that are related – taking care that the flow is correctly depicted by the direction of the arrowhead. For the placement of a KC, a double-headed arrow shows that the element is directionless. In this way, a user can construct a DFC of great complexity that will still remain manageable. Once all elements have been placed and connected, they can be dragged to new locations without fear of losing the linking relationships.

DFCCT: Complex Example

The example shown in Figure 10-4 demonstrates the fully constructed DFC depicted in an earlier chapter. Note that the actual physical placement of nodes and linkages is immaterial – only the relationships established by the connections are important. However, for reader simplicity this DFC has been laid out to mirror the manual DFC already discussed. As can be seen, one of the linkages has been selected (number 42) and its constraint properties are displayed. Any constraint reading true is assumed to be passed through this linkage.

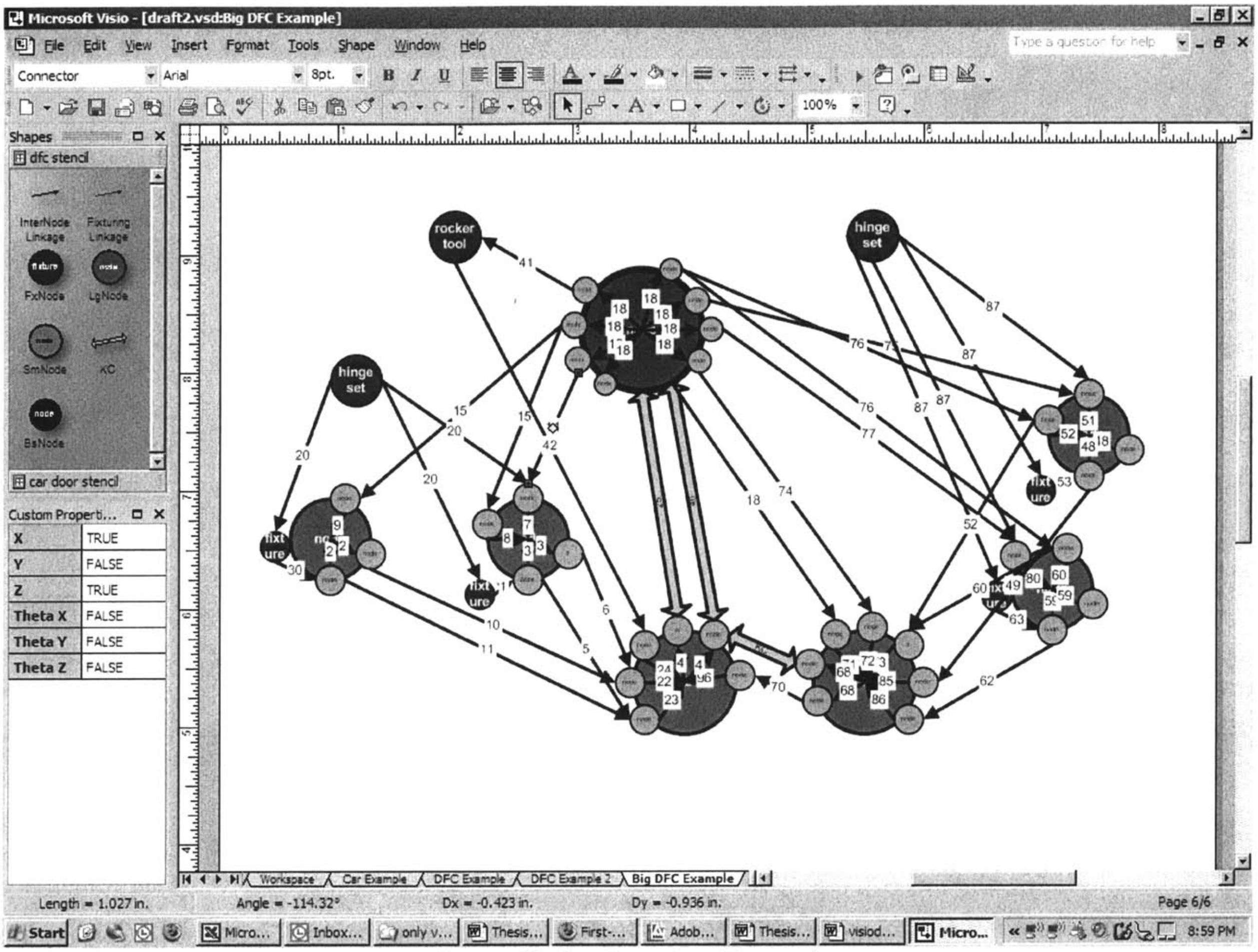


Figure 10-4: Complex Example

Performing DFCCT Analysis

In order to run analysis, the user must select the node of interest or KC of interest (depending on analysis type) and then choose one of the options on the DFC pull down menu. Analysis types include Constraint Analysis, Critical Path Analysis, KC Conflict Analysis, and Design Ratio Analysis. Various error messages will be displayed if the user has neglected some key aspect of the DFC construction. For a complete list of the code which runs these analyses, please consult Appendix I.

Suggestions for Future Work

The development of this software package is considered complete but with room for much additional improvement. Given the short time frame, there may yet be issues with the code that will require fixing and improving. More importantly, though, this package does not yet provide a means of flowing information quickly and easily into DVA for further analysis. Writing an additional module which could bridge the gap between the two would be of great value and may allow the beginnings of the DFC-DVA collaboration that Magna needs.

Beyond software development, there exists the need of systems leaders within Magna to continue the development and analysis of program specific DFC's in order to build comfort and confidence in their use. As these DFC's are built and catalogued, organizational momentum should begin to build, and the use of these techniques should spread.

Conclusion

Magna represents an organization which is becoming increasingly adept at the design of complex systems, but which is not progressing quickly enough to surpass their competitors. In order to speed their rate of learning and system improvement, it is recommended that the current CSI and PD CSI initiative be augmented with the use of enhanced toolsets. This thesis has set out to demonstrate how current engineers should foster a greater appreciation for the interrelated complexities found in second-order complex systems, and should pursue the development and use of tools that provide the firepower needed to apply this thinking to the design of Magna vehicles. In particular, the use of DVA and DFC was explored and the results from both were considered in light of the current design of Magna-duty trucks. Finally, the barriers to the use of DFC were explored and the development of software intended to ease the organization's transition was introduced. Ultimately, as with many such initiatives, Magna must work to reach an organizational tipping point such that enough in-house experts are using the proper tools and engaging in the proper thinking, that the company begins to transform itself from the inside out.

REFERENCES

- C. L. Magee, O. L. de Weck2, *Complex System Classification*, 14th Annual INCOSE symposium.

- Gray, J.M., "A Unified Approach to Modeling, Verifying, and Improving the Manufacturability of Mechanical Assemblies" SM Thesis, Massachusetts Institute of Technology, Mechanical Engineering Department, Cambridge, MA, 2002.

- J.D. Power and Associates 2003 Initial Quality Survey

- J.D. Power and Associates 2004 Initial Quality Survey

- Moccio, C., "Using Datum Flow Chain and Design Structure Matrix Manage Team Structure and Integration" SDM Thesis, Massachusetts Institute of Technology, System Design and Management Program, Cambridge, MA, 2002.

- Whitney, D.E., Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development, Oxford University Press, Oxford, England, 2004.

Code: Add DFC Toolbar to Visio

```
Sub toolbar_add()
Dim uiObj As Visio.UIObject
Dim visMenuSets As Visio.MenuSets
Dim visMenuSet As Visio.MenuSet
Dim visMenus As Visio.Menus
Dim visMenu As Visio.Menu
Dim visMenuItems As Visio.MenuItems
Dim visMenuItem As Visio.MenuItem
Set uiObj = Visio.Application.BuiltInMenus
Set visMenuSets = uiObj.MenuSets
' Get the Visio object context menu set.
Set visMenuSet = visMenuSets.ItemAtID(visUIObjSetDrawing)
Set visMenus = visMenuSet.Menus
' Set menu as #9 (new position after Help) and add menu called "DFC"
Set visMenu = visMenus.AddAt(9)
visMenu.Caption = "DFC"
visMenu.State = Visio.visButtonCaption
' Get the items collection from the DFC menu (empty at first)
 Set visMenuItems = visMenu.MenuItems
' Add option to clear links at first position in DFC menu
Set visMenuItem = visMenuItems.AddAt(0)
visMenuItem.Caption = "Reset Links"
visMenuItem.State = Visio.visButtonUp
' Associate KCCA with macro
visMenuItem.AddOnName = "Drawing1.Module2.clearlinks"
' Add Constraint State Anlysis at second position in DFC menu
Set visMenuItem = visMenuItems.AddAt(1)
visMenuItem.Caption = "Constraint State Analysis"
visMenuItem.State = Visio.visButtonUp
' Associate CSA with macro
visMenuItem.AddOnName = "Drawing1.Module3.constraintstate"
' Add Critical path anlysis at third position in DFC menu
Set visMenuItem = visMenuItems.AddAt(2)
visMenuItem.Caption = "Critical Path Analysis"
visMenuItem.State = Visio.visButtonUp
' Associate CPA with macro
visMenuItem.AddOnName = "Drawing1.Module2.analysistype1"
' Add KC Conflict Anlysis at fourth position in DFC menu
Set visMenuItem = visMenuItems.AddAt(3)
visMenuItem.Caption = "KC Conflict Analysis"
visMenuItem.State = Visio.visButtonUp
```

```
' Associate KCCA with macro
visMenuItem.AddOnName = "Drawing1.Module2.analysistype2"
' Add Design Ratio Anlysis at fourth position in DFC menu
Set visMenuItem = visMenuItems.AddAt(4)
visMenuItem.Caption = "Calculate Design Ratio"
visMenuItem.State = Visio.visButtonUp
' Associate KCCA with macro
visMenuItem.AddOnName = "Drawing1.Module4.design_ratio"
' Set the new menus.
Visio.Application.SetCustomMenus uiObj
' Tell Visio to use the new UI when the document is active.
ThisDocument.SetCustomMenus uiObj
End Sub
```

Code: Clear Last Run

```
Sub clearlinks()
Dim shpno As Integer
Dim shpObj As Visio.Shape
Dim shpName As String
' before we begin, must reset each link's path
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
shpName = shpObj.Name
If shpObj.OneD Then ' Only list the 1-D shapes
'If shpObj.Cells("User.visKeywords") = 83 Then 'ignore the KC arrow
'Else
' resets each link's path
Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
shpObj.Cells("user.visVersion") = 0
' resets each link's color
shpObj.Cells("linecolor") = 0
'End If
End If
Next shpno
End Sub
```

Code: For Critical Path Analysis and KC Conflict Analysis (combined as analysis 1 and 2)

```
Sub analysistype1()
Dim analysistype As Integer
analysistype = 1
Call kcnodes(analysistype)
End Sub
```

```
Sub analysistype2()
Dim analysistype As Integer
analysistype = 2
Call kcnodes(analysistype)
End Sub

Sub kcnodes(analysistype As Integer)
Dim objShps As Visio.Selection, objshp As Visio.Shape
Dim i As Integer, i2 As Integer
Dim numnode As Integer
Dim kcnodes(2) As Integer
Dim kcdofx(100) As Boolean, kcdofy(100) As Boolean, kcdofz(100) As Boolean
Dim kcdofTx(100) As Boolean, kcdofTy(100) As Boolean, kcdofTz(100) As Boolean
Dim bkcnodes(100) As Integer
Dim ekcnodes(100) As Integer
Dim totalkc As Integer
Dim myvalue As String
Set objShps = Visio.ActiveWindow.Selection
totalkc = objShps.Count
If analysistype = 1 Then
If objShps.Count > 1 Then
myvalue = MsgBox("Please Select Only a Single KC and restart analysis")
End
End If
End If
' count the total number of selected objects (should all be KCs)
For i = 1 To totalkc
Set objshp = objShps(i)
objshp.Text = objshp.ID
If objshp.Cells("User.visKeywords") = 83 Then
Else
myvalue = MsgBox("Please Select Only KCs and restart analysis")
End
End If
' set variable equal to each dof's boolean value
kcdofx(i) = objshp.Cells("Prop.Row_2")
kcdofy(i) = objshp.Cells("Prop.Row_3")
kcdofz(i) = objshp.Cells("Prop.Row_4")
kcdofTx(i) = objshp.Cells("Prop.Row_5")
kcdofTy(i) = objshp.Cells("Prop.Row_6")
kcdofTz(i) = objshp.Cells("Prop.Row_7")
' set numnode equal to the total number of items connected to each KC (must be 2)
'numnode = objShp.Connects.Count
'objShp.Text = numnode
   For i2 = 1 To 2
   If i2 = 1 Then
```

```
   bkcnodes(i) = objshp.Connects(i2).ToSheet.ID
   objshp.Text = bkcnodes(i)
   Else
   ekcnodes(i) = objshp.Connects(i2).ToSheet.ID
   objshp.Text = ekcnodes(i)
   End If
   Next i2
Next i
Call simplevisio(analysistype, totalkc, bkcnodes, ekcnodes, kcdofx, kcdofy, kcdofz, kcdofTx,
kcdofTy, kcdofTz)
End Sub

Sub simplevisio(analysistype As Integer, totalkc As Integer, bkcnodes() As Integer, ekcnodes()
As Integer, kcdofx() As Boolean, kcdofy() As Boolean, kcdofz() As Boolean, kcdofTx() As
Boolean, kcdofTy() As Boolean, kcdofTz() As Boolean)
Dim shShape As Visio.Shape, PaletteEntry As Integer, vcolors As Colors
Dim shshape2 As Visio.Shape
Dim begcon As String
Dim concolor As Integer
Dim avalue As String
Dim begnode As Integer
Dim endcon As String
Dim endnode As Integer
Dim fholder1 As String
Dim fholder2 As String
Dim fholder3 As String
Dim lwidth As Integer
Dim shpsObj As Visio.Shapes
Dim ShapesCnt As Integer
Dim shpObj As Visio.Shape
Dim begx(100) As String
Dim endx(100) As String
Dim shpName As String
Dim shpno As Integer
Dim numbegx(100) As Double
Dim fcount As Integer
Dim fbreakbegx As String
Dim fbreakendx As String
Dim begvaluecell As Integer
Dim endvaluecell As Integer
Dim path As Long
Dim pcount As Integer
Dim tierrowholder(10) As Integer ' this stores the row that we last considered for each tier
Dim tiervalueholder(10) As Integer ' this stores the value last considered for each tier
Dim valuecell As String
Dim tier As Integer
```

```
Dim strpath As String
Dim critpath(100) As String
Dim critpathcounter As Integer
Dim cpleg As String
Dim chop As Integer
Dim myvalue As String
Dim pathlength As Integer
Dim dofx(100, 100) As Boolean, dofy(100, 100) As Boolean, dofz(100, 100) As Boolean
Dim dofTx(100, 100) As Boolean, dofTy(100, 100) As Boolean, dofTz(100, 100) As Boolean
Dim dofmatch As Integer
Dim i As Integer
Dim nodeend As Integer
Dim kc As Integer
Dim connectsfrom As Integer
Dim connectsto As Integer
' before we begin, must reset each link's path
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
shpName = shpObj.Name
If shpObj.OneD Then ' Only list the 1-D shapes
If shpObj.Cells("User.visKeywords") = 83 Then 'ignore the KC arrow
Else
' resets each link's path
Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
shpObj.Cells("user.visVersion") = 0
' resets each link's color
shpObj.Cells("linecolor") = 1
End If
End If
Next shpno
For kc = 1 To totalkc
dofx(kc, 1) = kcdofx(kc)
dofy(kc, 1) = kcdofy(kc)
dofz(kc, 1) = kcdofz(kc)
dofTx(kc, 1) = kcdofTx(kc)
dofTy(kc, 1) = kcdofTy(kc)
dofTz(kc, 1) = kcdofTz(kc)
'receive node start and end values'
'begvaluecell = InputBox("What node are we starting at?", "BegValueCell", 5) ' for now, we're
looking for a path to extend back from 5
'endvaluecell = InputBox("What node are we ending at?", "EndValueCell", 2) ' for now, we're
looking for a path to extend to 2
' Set shpObj = Visio.ActivePage.Shapes.Item("fxnode.19")
' shpObj.Text = "hello"
For nodeend = 1 To 2
If nodeend = 1 Then
```

```
begvaluecell = bkcnodes(kc)
endvaluecell = ekcnodes(kc)
Else
begvaluecell = ekcnodes(kc)
endvaluecell = bkcnodes(kc)
End If
' set begvaluecell as value cell to check
' tier=1
' check at shpno=1 (if 1D)
' if not found then check for shpno=2
' if found then store previous valuecell as tier1valuecell and previous shpno as tier1shpno
' also mark a custom cell in this shape with a path (according to path rules)
' then set cor number as new value cell, reset shpno and start search again
valuecell = begvaluecell ' the first value we'll look for will be to start the path from 5
tier = 1
critpathcounter = 0
For i = 1 To 100
critpath(i) = ""
Next i
rowloop: ' beginning of row operations
fbreakbegx = "0"
fbreakendx = "0"
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
shpName = shpObj.Name
' shpObj.Text = ""
If shpObj.OneD Then ' Only list the 1-D shapes
If shpObj.Cells("User.visKeywords") = 83 Then 'ignore the KC arrow
Else
   connectsfrom = shpObj.Connects(1).ToSheet.ID
   shpObj.Text = ""
   'shpObj.Text = "22222222222"
   'shpObj.Text = connectsfrom
   If valuecell = connectsfrom Then
   GoTo dofgauntlet
   Else
   GoTo lowertier
   End If
End If
End If
lowertier:
Next shpno
tierreduce:
tier = tier - 1
If tier >= 1 Then
' reduce the path as we drop back a tier
```

```
strpath = path
pcount = Len(strpath)
strpath = Left(strpath, (pcount - 1))
path = strpath
shpno = tierrowholder(tier)
valuecell = tiervalueholder(tier)
GoTo lowertier
Else
GoTo endlabel
End If
dofgauntlet:
dofmatch = 0
'shpObj.Text = tier
'shpObj.Text = dofx(tier)
If dofx(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_1") = 1 Then
   dofx(kc, tier + 1) = True
   dofmatch = True
   Else
   dofx(kc, tier + 1) = False
   End If
End If
'shpObj.Text = shpObj.Cells("Prop.Row_2")
'shpObj.Text = shpObj.Cells("Prop.Row_3")
If dofy(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_2") = 1 Then
   dofy(kc, tier + 1) = True
   dofmatch = True
   Else
   dofy(kc, tier + 1) = False
   End If
End If
If dofz(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_3") = 1 Then
   'shpObj.Text = shpObj.Cells("prop.row_3")
   dofz(kc, tier + 1) = True
   dofmatch = True
   Else
   dofz(kc, tier + 1) = False
   End If
End If
If dofTx(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_4") = 1 Then
   dofTx(kc, tier + 1) = True
   dofmatch = True
   Else
```

```
   dofTx(kc, tier + 1) = False
   End If
End If
If dofTy(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_5") = 1 Then
   dofTy(kc, tier + 1) = True
   dofmatch = True
   Else
   dofTy(kc, tier + 1) = False
   End If
End If
If dofTz(kc, tier) = True Then
   If shpObj.Cells("Prop.Row_6") = 1 Then
   dofTz(kc, tier + 1) = True
   dofmatch = True
   Else
   dofTz(kc, tier + 1) = False
   End If
   'shpObj.Text = shpObj.Cells("Prop.Row_6")
End If
If dofmatch = True Then
GoTo valuefound
Else
GoTo lowertier
End If
valuefound:
   'let's forget about 'checking z' for right now
   ' we know this now counts as a path, let's give it a designation
      path = path + 1
   ' but first must set shpObj as current shapeno
      Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
      shpObj.Cells("User.visVersion") = path
      ' now let's store the number of this shape so we can continue our search later
      tierrowholder(tier) = shpno ' this needs to hold all tier's rows (can i index by tier #?)
      ' now let's store the value last considered for our return to this tier
      tiervalueholder(tier) = valuecell
      ' now let's check the corresponding number to set the search for our next path
      ' break beginy formula down to capture the last node number
         connectsto = shpObj.Connects(2).ToSheet.ID
         valuecell = connectsto
      ' if this number is the first node value we've been searching for, then this is a critical path.
mark it as such and abort current search
      'shpObj.Text = valuecell
      'shpObj.Text = endvaluecell
      If valuecell = endvaluecell Then
      critpathcounter = critpathcounter + 1
```

```
        critpath(critpathcounter) = path
        ' switch search value back to previous number, row is still set right
        valuecell = tiervalueholder(tier)
        GoTo lower
        Else
        ' now prepare the path for the next tier
        path = path & 0
        ' now we'll move to the next tier...
        tier = tier + 1
        GoTo rowloop
        End If
lower:
GoTo lowertier
endlabel:
' myvalue = InputBox("enter!")
' use Circle to display test values
' Set shpObj = Visio.ActivePage.Shapes.Item("Circle")
' shpObj.Cells("LineColor") = 0
' shpObj.Cells("User.visVersion") = 11
everypath:
critpathcounter = 0
critpathloop:
critpathcounter = critpathcounter + 1
chop = 0
foreachcritpath:
For shpno = 1 To Visio.ActivePage.Shapes.Count
    Set shpObj = Visio.ActivePage.Shapes(shpno)
    shpName = shpObj.Name
    pathlength = Len(critpath(critpathcounter))
        If pathlength = 0 Then
        GoTo endlabel2
        End If
        If pathlength = chop Then
        GoTo critpathloop
        End If
    cpleg = Left(critpath(critpathcounter), (pathlength - chop))
secondrowloop:
        If shpObj.OneD Then ' Only list the 1-D shapes
    Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
        If shpObj.Cells("User.visVersion") = cpleg Then
        If analysistype = 1 Then
        shpObj.Cells("linecolor") = 2
        Else
        If analysistype = 2 Then
        shpObj.Cells("linecolor") = (shpObj.Cells("linecolor") + 1)
        End If
```

```
      End If
      GoTo lowershow
      End If
      End If
lowershow:
   Next shpno
   chop = chop + 1
   GoTo foreachcritpath
endlabel2:
Next nodeend
Next kc
End Sub
```

Code: Used for Analysis of Constraint State

```
Sub constraintstate()
Dim objShps As Visio.Selection, objshp As Visio.Shape
Dim shShape As Visio.Shape, PaletteEntry As Integer, vcolors As Colors
Dim shshape2 As Visio.Shape
Dim begcon As String
Dim concolor As Integer
Dim avalue As String
Dim begnode As Integer
Dim endcon As String
Dim endnode As Integer
Dim fholder1 As String
Dim fholder2 As String
Dim fholder3 As String
Dim lwidth As Integer
Dim shpsObj As Visio.Shapes
Dim ShapesCnt As Integer
Dim shpObj As Visio.Shape
Dim begx(100) As String
Dim endx(100) As String
Dim shpName As String
Dim shpno As Integer
Dim numbegx(100) As Double
Dim fcount As Integer
Dim begvaluecell As Integer
Dim endvaluecell As Integer
Dim path As Long
Dim pcount As Integer
Dim tierrowholder(10) As Integer ' this stores the row that we last considered for each tier
Dim tiervalueholder(10) As Integer ' this stores the value last considered for each tier
Dim valuecell As String
```

```
Dim tier As Integer
Dim strpath As String
Dim critpath(100) As String
Dim critpathcounter As Integer
Dim cpleg As String
Dim chop As Integer
Dim myvalue As String
Dim pathlength As Integer
Dim dofx(100) As Boolean, dofy(100) As Boolean, dofz(100) As Boolean
Dim dofTx(100) As Boolean, dofTy(100) As Boolean, dofTz(100) As Boolean
Dim dofmatch As Integer
Dim i As Integer
Dim i2 As Integer
Dim nodeend As Integer
Dim kc As Integer
Dim connectsfrom As Integer
Dim connectsto As Integer
Dim cpdof(100, 6) As Boolean
Dim cpadd(6) As Integer
' before we begin, must reset each link's path
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
shpName = shpObj.Name
If shpObj.OneD Then ' Only list the 1-D shapes
If shpObj.Cells("User.visKeywords") = 83 Then 'ignore the KC arrow
Else
' resets each link's path
Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
shpObj.Cells("user.visVersion") = 0
' resets each link's color
shpObj.Cells("linecolor") = 0
End If
End If
Next shpno
'set all part dofs to yes (should be fully constrained)
dofx(1) = 1
dofy(1) = 1
dofz(1) = 1
dofTx(1) = 1
dofTy(1) = 1
dofTz(1) = 1
'set part id as starting point
Set objShps = Visio.ActiveWindow.Selection
Set objshp = objShps(1)
valuecell = objshp.ID
If objShps.Count > 1 Then
```

```
myvalue = MsgBox("Please Select Only a SINGLE node and restart analysis")
End
End If
If objshp.Cells("user.viskeywords") = 81 Then
myvalue = MsgBox("Please Select Only a single NODE and restart analysis")
End
End If
If objshp.Cells("User.visKeywords") = 83 Then
myvalue = MsgBox("Please Select Only a single NODE and restart analysis")
End
Else
If objshp.Cells("user.viskeywords") = 89 Then
myvalue = MsgBox("Please Select a NON-BASE node and restart analysis")
End
End If
End If
'set base part id as ending point
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
If shpObj.Cells("User.visKeywords") = 89 Then
endvaluecell = shpObj.ID
End If
Next shpno
tier = 1
critpathcounter = 0
For i = 1 To 100
critpath(i) = ""
Next i
rowloop: ' beginning of row operations
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set shpObj = Visio.ActivePage.Shapes(shpno)
shpName = shpObj.Name
' shpObj.Text = ""
If shpObj.OneD Then ' Only list the 1-D shapes
If shpObj.Cells("User.visKeywords") = 83 Then 'ignore the KC arrow
Else
  connectsto = shpObj.Connects(2).ToSheet.ID
  connectsfrom = shpObj.Connects(1).ToSheet.ID
  shpObj.Text = "22222222222"
  shpObj.Text = connectsto
  shpObj.Text = connectsfrom
  If valuecell = connectsto Then
  GoTo dofgauntlet
  Else
  GoTo lowertier
  End If
```

```
End If
End If
lowertier:
Next shpno
tierreduce:
tier = tier - 1
If tier >= 1 Then
' reduce the path as we drop back a tier
strpath = path
pcount = Len(strpath)
strpath = Left(strpath, (pcount - 1))
path = strpath
shpno = tierrowholder(tier)
valuecell = tiervalueholder(tier)
GoTo lowertier
Else
GoTo endlabel
End If
dofgauntlet:
dofmatch = 0
'shpObj.Text = tier
'shpObj.Text = dofx(tier)
If dofx(tier) = True Then
   If shpObj.Cells("Prop.Row_1") = 1 Then
   dofx(tier + 1) = True
   dofmatch = True
   Else
   dofx(tier + 1) = False
   End If
End If
shpObj.Text = shpObj.Cells("Prop.Row_2")
shpObj.Text = shpObj.Cells("Prop.Row_3")
If dofy(tier) = True Then
   If shpObj.Cells("Prop.Row_2") = 1 Then
   dofy(tier + 1) = True
   dofmatch = True
   Else
   dofy(tier + 1) = False
   End If
End If
If dofz(tier) = True Then
   If shpObj.Cells("Prop.Row_3") = 1 Then
   shpObj.Text = shpObj.Cells("prop.row_3")
   dofz(tier + 1) = True
   dofmatch = True
   Else
```

```
    dofz(tier + 1) = False
    End If
End If
If dofTx(tier) = True Then
    If shpObj.Cells("Prop.Row_4") = 1 Then
    dofTx(tier + 1) = True
    dofmatch = True
    Else
    dofTx(tier + 1) = False
    End If
End If
If dofTy(tier) = True Then
    If shpObj.Cells("Prop.Row_5") = 1 Then
    dofTy(tier + 1) = True
    dofmatch = True
    Else
    dofTy(tier + 1) = False
    End If
End If
If dofTz(tier) = True Then
    If shpObj.Cells("Prop.Row_6") = 1 Then
    dofTz(tier + 1) = True
    dofmatch = True
    Else
    dofTz(tier + 1) = False
    End If
    shpObj.Text = shpObj.Cells("Prop.Row_6")
End If
If dofmatch = True Then
GoTo valuefound
Else
GoTo lowertier
End If
valuefound:
    ' we know this now counts as a path, let's give it a designation
        path = path + 1
    ' but first must set shpObj as current shapeno
        Set shpObj = Visio.ActivePage.Shapes.Item(shpName)
        shpObj.Cells("User.visVersion") = path
        ' now let's store the number of this shape so we can continue our search later
        tierrowholder(tier) = shpno ' this needs to hold all tier's rows (can i index by tier #?)
        ' now let's store the value last considered for our return to this tier
        tiervalueholder(tier) = valuecell
        ' now let's check the corresponding number to set the search for our next path
        ' break beginy formula down to capture the last node number
            connectsfrom = shpObj.Connects(1).ToSheet.ID
```

```
        valuecell = connectsfrom
      ' if this number is the first node value we've been searching for, then this is a critical path.
mark it as such and abort current search
      shpObj.Text = valuecell
      shpObj.Text = endvaluecell
      If valuecell = endvaluecell Then
      'increment counter
      critpathcounter = critpathcounter + 1
      critpath(critpathcounter) = path
      'store collection of dof for this critical path
      cpdof(critpathcounter, 1) = dofx(tier + 1)
      cpdof(critpathcounter, 2) = dofy(tier + 1)
      cpdof(critpathcounter, 3) = dofz(tier + 1)
      cpdof(critpathcounter, 4) = dofTx(tier + 1)
      cpdof(critpathcounter, 5) = dofTy(tier + 1)
      cpdof(critpathcounter, 6) = dofTz(tier + 1)
      ' switch search value back to previous number, row is still set right
      valuecell = tiervalueholder(tier)
      GoTo lower
      Else
      ' now prepare the path for the next tier
      path = path & 0
      ' now we'll move to the next tier...
      tier = tier + 1
      GoTo rowloop
      End If
lower:
GoTo lowertier
endlabel:
everypath:
For i = 1 To 6
cpadd(i) = 0
For i2 = 1 To critpathcounter
'myvalue = InputBox(cpdof(i2, i))
cpadd(i) = cpdof(i2, i) + cpadd(i)
objshp.Text = cpadd(i)
Next i2
Next i
myvalue = MsgBox(-cpadd(1), , "Constraint State for X")
myvalue = MsgBox(-cpadd(2), , "Constraint State for Y")
myvalue = MsgBox(-cpadd(3), , "Constraint State for Z")
myvalue = MsgBox(-cpadd(4), , "Constraint State for TX")
myvalue = MsgBox(-cpadd(5), , "Constraint State for TY")
myvalue = MsgBox(-cpadd(6), , "Constraint State for TZ")
End Sub
```

Code: Design Ratio used for outputting design metrics

```
Sub design_ratio()
Dim objshp As Visio.Shape
Dim shpno As Integer
Dim linkagecounter As Integer
Dim nodecounter As Integer
Dim myvalue As Integer
Dim designratio As Double
Dim drstring, totalMsg, textMsg As String
linkagecounter = 0
nodecounter = 0
For shpno = 1 To Visio.ActivePage.Shapes.Count
Set objshp = Visio.ActivePage.Shapes(shpno)
If objshp.OneD Then
linkagecounter = linkagecounter + 1
Else
nodecounter = nodecounter + 1
End If
Next shpno
designratio = linkagecounter / nodecounter
designratio = FormatNumber(designratio, 3)
drstring = designratio
textMsg = "This assembly's design ratio is:"
totalMsg = textMsg & drstring
myvalue = MsgBox(totalMsg)
End Sub
```