Seisan! Ichi...Ni...San! The Kick of Design for Six Sigma in the Automotive Industry

by

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Abstract

In today's aggressive business environment, many manufacturing firms are searching for new strategies or methodologies that will provide some type of competitive advantage. Recently, in order to address that issue, the automotive industry has adopted the process of Design for Six Sigma (DFSS). Based upon the philosophies of Six Sigma quality management, Design for Six Sigma focuses on the design and research phases of product design, as its name implies. Consequently, to accurately identify the customer requirements, the Design for Six Sigma process insists upon data-driven design decisions coherent with the consumer defined quality metrics.

While the concepts of Design for Six Sigma and Six Sigma in general have been very successful for a number of large manufacturing firms such as General Electric and Motorola, it is not clear whether it will offer the same benefits for the automotive industry. Using the Parallel Hybrid Truck Program at General Motors Corporation, the largest US automotive manufacturer, as a case study, the implementation of Design for Six Sigma within the automotive industry is explored.

It is obvious Design for Six Sigma will provide both advantages and disadvantages. Therefore, in order for Design for Six Sigma to be successful in the automotive industry, the following insights need to be captured and delivered upon. Leadership must be strong and demonstrate a consistent commitment to the process. Both the technical and cultural elements of the process need to be implemented successfully. Integration of Design for Six Sigma needs to occur with current improvement efforts, and coordination of efforts between various groups in the organization needs to exist. Interestingly, these are classical problems facing the automotive industry for many years now, and they require a complete paradigm shift from the current automotive practices in order to be successful.

Furthermore, to better substantiate the impact of Design for Six Sigma, the following improvements to the standard Six Sigma practices and strategy are recommended. A high level manufacturing position should be created to complement the product engineering representative for the DFSS process. In addition, DFSS projects should be encouraged from the Manufacturing Organization to create buy-in and to leverage their day-to-day understanding of the product issues. Finally, like product specifications, Design for Six Sigma specifications should follow a product through the design cycle.

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Chapter 1  Introduction

Karate, the Okinawan fighting art that has spread from Japan across the world, has received much fame. In Okinawan, karate means “Chinese Hands”, but when translated into Japanese it means “Empty Hands”. Karate was at first a “jitsu” system, a system made for the battlefield. Initially, it was used by the peasants in Okinawa to protect themselves from the samurai and muggers. If one was unable to defend himself, he would be killed by the attacker; therefore, karate was introduced and widely accepted.

Today, karate is a “do” system, which is a life long system used to perfect oneself. In fact, to test skills and perfection, some brave Karate-ka (karate students) will face huge tidal waves and fierce storms. (“Karate”)

In today’s aggressive business environment though, many manufacturing firms are in the position of the Karate-ka, as they face the fierce storms of quality, profitability, and longevity from competitors. In the early 1990’s, Motorola termed their Karate-ka, those possessing special expertise in statistics and product or process improvement in the Six Sigma system, as “black belts” (Pande, Neuman, and Cavanagh123). Of course, the “black belt” label was drawn from the martial arts, as it suggests a finely honed skill and discipline in training and experience.

That leads to the title of this thesis- “Seisan! Ichi...Ni...San! The Kick of Design for Six Sigma in the Automotive Industry”. Seisan¹, a formal exercise of true Karate-Do, literally translates as "thirteen hands". It contains 8 defensive and 5 offensive techniques, both of which involve a change in direction. Seisan stresses close range fighting using short punching and low kicking techniques to break through an opponent’s defenses. Seisan is an extremely important karate technique, and it has a wealth of knowledge and information contained within it. Typically, while practicing this form of Karate-Do, the master or wise, experienced teacher will yell out “Seisan! Ichi (one)....Ni (two)… San (three)…” and so on, as he proceeds through each of the moves.

In this thesis, the “kick” or revolution of Design for Six Sigma and the Six Sigma philosophies in the automotive industry will be explored. In Chapter 2, the details and history of the process will be summarized. Chapter 3 will focus on a specific case study implementing Design for Six Sigma at General Motors Powertrain. Chapter 4 will discuss the cultural and technical elements required for a corporation to be successful at DFSS. Chapter 5 will present specific advantages and disadvantages for the American automotive industry. And finally, the conclusions will be presented in Chapter 6.

As a whole, this thesis provides an overview of Design for Six Sigma with specific applicability to the automotive industry while addressing the pros and cons of the process for the near future of the industry. Throughout this work, since the principles of DFSS are based in Six Sigma, the term Design for Six Sigma and Six Sigma will be utilized interchangeably when the discussion focuses only on the general principles.
Chapter 2  Design for Six Sigma

By definition, Design for Six Sigma or DFSS is a methodology for creating product and process designs to meet the customer needs. Within the DFSS process, General Electric claims that "customers are the center of the universe; they define quality". At first glance, focusing on the customers needs may sound obvious and simplistic. But, with the depth of the DFSS process, it is a truly profound realization for many manufacturing firms.

2.1  Design for Six Sigma ≠ Manufacturing Six Sigma

Design for Six Sigma is based upon the fundamental concepts of Six Sigma engineering quality or 3.4 defects out of every 1 million opportunities, hence its name. However, the process title typically creates two kinds of confusion. First many assume Design for Six Sigma project goals are 6-sigma quality, when in fact, projects goals vary from 4-sigma for nuisance items to greater than 6-sigma quality for safety issues. The second point of confusion stems from the failure of many to differentiate between DFSS and manufacturing Six Sigma. The fact of the matter is both process are very different.

With Design for Six Sigma, customers define the level of quality through metrics such as customer complaints. In some cases, true Six Sigma quality may be unnecessary for certain design or process elements. On the other hand, DFSS may indicate that the customer’s needs cannot be achieved long-term; therefore, the design or process must be changed to satisfy the customer. With Design for Six Sigma, these changes can be implemented early in the design phase. Unlike traditional Six Sigma manufacturing quality, DFSS moves the quality effort to the research/design phases where defects are more difficult to identify but easier to correct economically (see Figure 2.1). Currently though, most Six Sigma quality effort is focused on production and manufacturing tolerances. While these efforts prevent defects from getting to the customer, they do not prevent them from occurring in the first place.

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2 Much of this chapter was derived from the General Motors Corporation Design for Six Sigma Project Team Training manual.
2.2 The Design for Six Sigma Process

For most Six Sigma processes, a generic five-phase improvement cycle has been defined as DMAIC (pronounced “deh-MAY-ihk”) or Define, Measure, Analyze, Improve, and Control. The DMAIC cycle can be applied to both process improvement or process/product design or redesign efforts, but it is typically utilized for more traditional applications of Six Sigma. Therefore, Dr. Maurice Berryman standardized the Design for Six Sigma process to specifically apply to the design/research phases (General Motors Corporation 15). The four main steps of the DFSS include the following:

1) Critical to Quality (CTQ) Flow Down
2) Quality Prediction
3) Optimize Design
4) Test and Verify

In step one, critical to quality or CTQ is defined as an element of a design essential to quality from the customer's viewpoint. Therefore, CTQ flow down requires identification of the problem and identification of the customer CTQs on the subsystem level. Step two requires identification of the performance targets for each CTQ and generation of a transfer function or model. Typically, step two is the longest portion of the DFSS process, since the transfer functions tend to be complex interpretations of unexplored arenas. Step three evaluates whether the proposed design meets the quality targets, based upon the parameter variations determined in step two. Also during step three, the critical parameters are communicated to the manufacturers
and suppliers, and control plans are developed. In the final step, a pilot is built to confirm the model's prediction, and the model is refined accordingly. Details of the standardized Design for Six Sigma Process can be found in Appendix A.

2.3 **Key Benefits of Design for Six Sigma**

In statistical terms, the Greek symbol sigma is used to define the standard deviation or variation of a population. Everything varies to some degree, but variation from a manufacturer's perspective is a cause for concern. GE claims "customers feel the variance, not the mean". As variation increases, quality decreases, and the customer becomes dissatisfied with the product.

Therefore, there is continuous trade-off between cost, quality, and customer satisfaction; but DFSS focuses on the optimal design, the point where the customer’s needs are comfortably met (See Figure 2.2). When products are designed and manufactured with the minimum variations for critical elements, customers will become loyal, market share will be maintained or increase, and margins will also increase.

![Figure 2.2 Design for Six Sigma Optimal Design Trade-Offs (General Motors Corporation)](image)

Although there are a multitude of benefits for using Design for Six Sigma, to many the most important benefit is financial. In fact, many noteworthy companies have reported financial savings in billions of dollars for using the basic Six Sigma principles. While this number may
appear astounding, after all DFSS is just a quality improvement process, profit loss due to poor quality can be dramatic. In fact, a number of studies by top business schools estimate a typical company suffers an annual profit loss due to poor quality that is on the order of 25% of revenues (Revinus).

Overall though, Design for Six Sigma will reduce defects, reduce cycle times, reduce inventory levels, increase efficiency, and decrease costs. Also, many companies adopting DFSS experience a fundamental cultural shift. Instead of making decisions based on personal biases, companies are forced to be objective and make data-driven decisions; this also prevents over-engineering of products or processes, which seems to be quite natural for many engineering and manufacturing firms. In addition to these benefits, since DFSS is such a customer-focused process, customer satisfaction will increase significantly. In turn, higher market share can be gained, and eventually, greater profits are realized.

2.4 History of Six Sigma Philosophies

Many believe that the concepts of Six Sigma quality began with the statistical process control teachings of Deming. The Japanese in particular were quick to adopt these methodologies, turning them into a philosophical concept encompassing all aspects of business. As the Japanese became financially successful, the ideas of quality management for manufacturing were introduced to the rest of the world.

In 1981, Motorola’s Chairman Bob Galvin implemented the fundamental concepts of Six Sigma in the manufacturing environment. Galvin was fed up with the focus on Japanese quality; instead, he felt that Motorola could exceed Japanese quality by focusing on achieving 6-sigma quality targets instead of the traditional 3 or 4 sigma targets. Motorola implemented a system to support the improved quality targets, achieving a recordable 5.5-sigma level and saving the company $2.2 billion through the process (Revinus). In addition, two years after implementing Six Sigma, Motorola was honored with the Malcolm Baldrige National Quality Award, and profits grew nearly 20 percent per year (Pande, Neuman, and Cavanagh 7).

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3 The history of Six Sigma was derived from The Six Sigma Way: How GE, Motorola, and Other Top Companies Are Honing Their Performance.
In 1989, a group of manufacturing firms gathered and supported the Six Sigma Research Institute. There, the conceptual details and terminology were developed. In 1993, ABB and Texas Instruments implemented the Six Sigma philosophy. But, in 1994, Allied Signal deployed a different kind of Six Sigma; not only was Allied Signal’s Six Sigma focused on manufacturing quality, but it was also focused on the entire business including aspects such as finance and management. Based upon the statistical problem solving tools developed at Motorola, Allied Signal developed a corporate focus on the Six Sigma, implementing a corporate structure necessary to support the new way of business.

Enamored of the success of many Six Sigma firms, Jack Welch, the Chairman and CEO of General Electric, began to study Six Sigma. In 1995, GE adopted the Six Sigma philosophy corporate wide. Jack Welch said the following:

“Six Sigma has forever changed G.E. Everyone- from the Six Sigma zealots emerging from their Black Belt tours, to the engineers, the auditors, and the scientists, to the senior leadership that will take this company into the next millennium- is a true believer in Six Sigma, the way this company now works.”

(Pande, Neuman, and Cavanagh 4)

At General Electric, a Six Sigma lighting unit repaired problems in billing to its top customer, Wal-Mart, cutting invoice defects and disputes by 98 percent. Using Design for Six Sigma, GE’s Medical Systems business created a breakthrough medical scanning technology that scans the full-body in less than 30 seconds. And, in GE Capital Mortgage, the top-performing branch improved the rate of a caller reaching a “live” operator from 76 to 99 percent.4

2.5 Design for Six Sigma & The American Automotive Industry

Recently, Six Sigma has become a rapidly adopted business strategy by some of the world’s most respected companies. With the much-publicized successes of General Electric, many firms have realized Design for Six Sigma improves the capacity to satisfy customer needs, gain customer loyalty, and improve the effectiveness of processes. Also, unlike the entire Six Sigma

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4 The General Electric improvements plus additional GE specific examples can be found in Chapter 1 of The Six Sigma Way: How GE, Motorola, and Other Top Companies Are Honing Their Performance.
strategy, Design for Six Sigma is a portion of the process that focuses on prevention by focusing on the early design phases. For all of these reasons, the automotive industry has adopted the Design for Six Sigma strategy over the past few years.

2.5.1 General Motors\(^5\)

General Motors Global Manufacturing System focuses heavily on quality through the following three major initiatives: quality planning, quality control, and quality improvement. For each of the three major initiatives, a specific quality plan exists which includes concepts such as Design and Failure Mode and Effects Analysis for Quality Planning, In-Process Control for Quality Control, and Red X Strategies for Quality Improvement. Furthermore, each of the three initiatives utilizes the concepts of Six Sigma Capability, Common Processes, QS-9000 Certification, and the Quality Network Foundation.

Six Sigma itself has been successful within all of General Motors' divisions. For instance, Delphi, previously owned by General Motors, has captured a significant amount of value from the process. Delphi has focused heavily on training, with even executives participating in 40 hours of Green-Belt training. And, that training and experience has paid off. In Delphi Packard Electric's India operations, application of Six Sigma tools improved first time quality by 91 percent and gained $76,000 in savings.

In 1999, General Motors adopted Design for Six Sigma as part of the Quality Planning initiative. GM issued the following mandate for 2000 with respect to DFSS: “DFSS must be the way we do work in the vehicle development process within one year”. General Motors hopes that Design for Six Sigma will create a greater, but required focus on quality, improve the J.D. Powers gap with competitors, reduce high warranty vehicle programs, and most importantly, increase GM's market share.

\(^5\) The information for General Motor's adoption of Six Sigma was derived from the GM intranet news postings.
2.5.2 Ford

In order to achieve the corporate vision of becoming a consumer products company and to gain an increase in customer satisfaction, Ford adopted the Six Sigma philosophies in 1999. Phong Vu, who is responsible for Ford’s deployment of Consumer Driven Six Sigma, viewed Six Sigma as a perfect method to achieve the company’s twin goals of improving customer satisfaction while also improving quality.

Louie Goeser, Ford’s vice president of quality, said “We put together a plan to implement Six Sigma throughout the whole company in October 1999 with a couple of leading groups. In December 1999 and January 2000, the top management went through executive training.” Jacques Nassar, then Ford CEO, went through the Six Sigma training, and he also regularly championed projects.

In the first year and a half of implementation, Ford trained nearly 10,000 employees in the Six Sigma philosophies. Employees were trained a variety of levels including Master Black Belts, Black Belts, and Green Belts. With more than 2,500 Black Belts in September of 2001, Ford’s goal was to train all of the salaried professionals to be Green Belts by 2005.

Ford selects Six Sigma projects based on the following three criteria: must relate to customer satisfaction, must reduce defects by at least 70 percent, and should average $250,000 in cost-savings. Since Ford has adopted both Six Sigma and Design for Six Sigma techniques, they have chosen to implement the generic DMAIC (Design, Measure, Analyze, Improve, Control) process structure.

Like any new corporate change, the Six Sigma adoption at Ford has been challenged culturally. For instance, employees were naturally skeptical of the process. Ford hopes to address that issue with time and continued corporate commitment. Commitment of resources has also been an issue to implementation; with the intense corporate training and already committed people, it has been difficult for the organization to maintain an acceptable balance. Finally, the infrastructure

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*Ford’s history and success of Six Sigma was derived from the article of Scott M. Paten titled “Consumer-Driven Six Sigma Saves Ford $300 million”.*
at Ford has been a challenge to the Six Sigma culture. Within the Six Sigma culture, decisions are data-driven, and often at Ford, some of the data simply was never measured. Ford addressed that issue by creating the necessary measurement systems. In addition, the accessibility of data has also been a roadblock. But, with more and more Six Sigma trained individuals spreading throughout the organization, this issue slowly has been dwindling away.

With all of the necessary implementation, including addressing the barriers to success, Ford has invested more than the $6 million required for the training license from the Six Sigma Academy. But, in 2000, Consumer Driven Six Sigma contributed $52 million to Ford’s bottom line, to demonstrate a very impressive return on investment. Ford has implemented Design for Six Sigma as their secondary phase of Consumer Driven Six Sigma, and it has leveraged the system already in place for the basic Six Sigma implementation.
Chapter 3  The GM Parallel Hybrid Truck: A Case Study

In order to better understand the implementation of Design for Six Sigma at General Motors, the present study was conducted using the Parallel Hybrid Truck (PHT) Program as its subject.

3.1 Environmental & Economic Motivation for the Parallel Hybrid Truck

In 2001, the American Petroleum Institute reported the US demand for gasoline in the first six months averaged 8.4 million barrels a day, up 0.9 percent from the previous year (Mateja). At the same time, higher energy prices caused US producers to raise crude oil production to 5.8 million barrels a day, an increase of 0.4 percent from 2000 (Mateja). Therefore, the US alone cannot meet its own demand; this not only puts a greater emphasis on foreign oil suppliers, but it also demonstrates concern for the world’s supply of gasoline. This has been one of the motivations for the US government’s demand for more fuel-efficient vehicles.

In July 2001, Dennis Minano, GM’s vice president for environment and energy, presented a campaign to Congress against raising fuel-efficiency standards. Minano claimed, “You’ve probably tweaked as much as you can from the internal combustion engine. Instead of focusing on CAFÉ standards, Congress should offer tax credits to consumers purchasing alternative powertrain vehicles (Hudson).” The bill Minano was opposing would require that SUVs, minivans, and light pickups be used in determining average fleet mileage.

Even though some do not support an increase in fuel economy standards, many believe it is reasonable and fair. For instance, the Union of Concerned Scientists urged Congress to boost the fuel-efficiency standards from 27.5 to 40 mpg by 2012 (Hudson). In addition, the National Academy of Sciences reported that US automakers could increase car and sport utility vehicle fuel economy by 33 percent in the next 15 years without raising the cost to consumers (Page).

But, from the automakers perspective, at current fuel prices, major fuel economy improvements across a manufacturer’s entire product line could be a very risky strategy. That is, the potential pay-off is likely to be small relative to the risk incurred. Because fuel savings accrue as a stream

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7 Much of the data for the GM Parallel Hybrid Truck program case study is considered proprietary. Therefore, it has been masked accordingly.
of future benefits, their discounted present value is, in theory, the appropriate measure of economic value to the consumer. However, the discount rate omits the fact that a dollar invested in a more expensive but more efficient vehicles will depreciate over time eventually to zero. Therefore, the dollar invested in fuel efficient technology will be worth less than a dollar if and when the owner sells the vehicle; in turn, the future fuel savings must be discounted at a rate substantially higher than the opportunity cost of capital to allow for recouping the original investment.⁸

With the automakers understanding the customer perspective and their potential risk, more and more have chosen to introduce a moderate fuel saving technology as a low-volume production. That is the basis for the introduction of the GM Parallel Hybrid Truck.

3.2 Parallel Hybrid Truck Technology

The hybrid vehicle is a technological solution to increasing fuel economy demands. In addition to using the traditional internal combustion engine as a power source, hybrid vehicles use an onboard generator to recharge the vehicle’s batteries. There are two primary types of hybrid vehicles- parallel and series. In the series type, a gasoline engine drives a generator that charges the batteries; in turn, the batteries power the electric motor that propels the vehicle. In contrast, for a parallel hybrid vehicle, the gasoline engine can also propel the vehicle via a direct mechanical linkage to the drive shaft.

The General Motors Hybrid Truck leverages the parallel hybrid design. It offers fuel economy savings through the following mechanisms:

- Decel-fuel cut-off (DFCO): in the event of vehicle deceleration, engine fueling can be disengaged. With the parallel hybrid truck, the electric machine creates torque smoothing, making the DFCO event unnoticeable to the driver.
- Engine off at idle: during optimal conditions, the engine can be completely shut off, and the electric motor can power the vehicle electrical loads. An example of when automatic engine shut-off may be utilized is a vehicle stopped at a red light.

⁸ The above economic analysis is from the work of David L. Green and John DeCicco in “Engineering-Economic Analyses of Automotive Fuel Economy Potential in the United States.”
- Regenerative braking: instead of allowing the brake to absorb and dissipate all of the kinetic energy for stopping, the electric motor can assist in slowing the vehicle. This allows the hybrid vehicle to capture some of the braking energy, as the electric motor charges the batteries during this slow down event.

The Parallel Hybrid Truck will be introduced as a GM light-duty full-size truck, the Chevrolet Silverado and GMC Sierra. The main goals of the truck program are to 1) maximize fuel economy, 2) minimize cost, and 3) maintain current truck performance and utility for the consumer. The Parallel Hybrid Truck is considered to be a “mild hybrid technology.”

3.3 Design for Six Sigma Process

3.3.1 Critical to Quality Flow Down

For the Parallel Hybrid Truck Program, the main problem or opportunity to be addressed with the Design for Six Sigma (DFSS) process was the following:

**to minimize the number of customer complaints for insufficient fuel economy due to vehicle-to-vehicle variation, specifically after vehicle break-in or 4000 miles on the GM Parallel Hybrid Truck.**

The project will focus on issues unique to the PHT powertrain that contribute to fuel economy variation. Variation due to customer driving patterns will not be considered but rather referenced to the Federal Test Procedure (FTP)\(^9\) driving cycle. In addition, the proposed solutions to reduce variation must not have a negative impact on customer-level functionality or quality, reliability, and durability (QRD).

Once the project focus and issues were determined, it was important to capture the rationale for the project. General Motors identifies the following key areas as motivation for a Design for Six Sigma project: quality, technology, and market. For the Parallel Hybrid Truck project under the realm of quality, motivation primarily existed to improve J.D. Power and Associates' ratings. Specifically, J.D. Power and Associates rates and ranks vehicles in a category known as Excessive Fuel Consumption; this rating was directly correlated to the Parallel Hybrid Truck

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\(^9\) Federal government regulations require automakers to certify vehicles according to the FTP - Federal Test Procedure. For the purpose of fuel economy certification, FTP requires the Environmental Protection Agency's testing protocol for transient vehicle testing using a vehicle dynamometer.
DFSS project focus. Since PHT consumers would primarily invest in the technology due to the improved fuel economy, customers would have higher expectations and a heightened awareness of the vehicle’s actual fuel economy. This exemplifies the need to deliver consistent fuel economy vehicle to vehicle.

In the area of technology, the Parallel Hybrid Truck was a new technology risk. Therefore, Design for Six Sigma could be used as a tool to reduce some of the risk. Finally, in the area of market, the Parallel Hybrid Truck needed to be a market win. General Motors developed the vehicle to excite the market, in efforts to gain more market share. Therefore, a robust first design for the market would be critical to the success of the overall project. Customers should not be able to notice or feel any objectionable mechanical differences between a Parallel Hybrid Truck and a standard truck; but the customer should be able to notice the significant fuel economy benefits of the Parallel Hybrid Truck.

Based upon the opportunity at hand, the customer Q’s or customer quality issues were defined. During a team brainstorming session, all of the possible customer Q’s were determined to be the following: the PHT should have a) consistent fuel economy vehicle-to-vehicle, b) consistent fuel economy for the same vehicle over time, c) consistent fuel economy with the advertised fuel economy, d) high fuel economy, e) a long range between fill-ups, and f) an actual fuel economy that matches the calculated or displayed fuel economy. Many of the customer Q’s were out of the scope of the Parallel Hybrid Truck DFSS Team; for instance, the DFSS (Powertrain) team had no influence on fuel tank design. That remained the responsibility of the Vehicle Team. On the other hand, many of the customer Q’s identified were within the scope of the Design for Six Sigma team, but other GM Powertrain groups were already addressing those issues (i.e. high fuel economy was the focus for several engineers over the past few years). Therefore, it was deduced that the customer Q of consistent fuel economy vehicle-to-vehicle best represented the issue at hand.

Focusing on the chosen customer Q, the next step was to identify the critical to quality parameter or CTQ. CTQ can be defined as the element of a design or the characteristic of a part that is essential to quality in the eyes of the customer. In other words, the CTQ captures the element
that affects the perceived value to the customer. For the purpose of the Parallel Hybrid Truck project, the CTQ identified was the actual variation in combined or composite\textsuperscript{10} fuel economy vehicle-to-vehicle. In order to better understand the PHT customers needs, an in depth analysis was completed of the current 2001 J.D. Power and Associates verbatims. For the purpose of this analysis, only 2001 GM Silverado and Sierra two-wheel drive, 5.3-liter engine, automatic transmission, full-size trucks were studied.

Verbatims are simply hand written comments by the customers. Not only do they provide an understanding of the customer’s perspective, but they also supply very useful data. For instance, in the area of Excessive Fuel Consumption, customer verbatims indicated that customers were indeed calculating their vehicle’s actual fuel economy; from 63 verbatims, 52 reported numerical values of fuel economy. The fact that customers were so in tune with their vehicle’s real fuel economy was at first very surprising to the Parallel Hybrid Truck DFSS team. From Figure 3.1, it is clear the current truck owners were experiencing a wide range of fuel economy values. For instance, the range of customer-determined fuel economies was from 9.5 to 19 MPG (miles per gallon) for composite fuel economy; note, this is for a vehicle that has an advertised sticker of 16.8 MPG composite.

![Figure 3.1 Verbatim Reported Fuel Economies](image)

In addition to understanding the verbatim data, the Design for Six Sigma team also studied the origin of the customer complaint. Interestingly, only 38% of customer complaints referred to the

\textsuperscript{10} Composite fuel economy is the harmonic average of the city and highway fuel economies. Mathematically \[ F_{\text{composite}} = \frac{0.55}{F_{\text{city}}} + \frac{0.45}{F_{\text{hwy}}} \].
advertised sticker value. While that is not conclusive data, it does indicate that many consumers reach fuel economy expectations through alternative, external means. For example, from the verbatims studied, 56% of customer complaints referenced fuel economy of a previously owned vehicle. Often, it was a previous model year. In some rare cases, consumers actually referred to an entirely different class of vehicles. In one specific case for example, a customer claimed that his or her fuel economy for the Sierra full-size truck was much less than that of his small car. While this learning does not fit well with the scope of the Design for Six Sigma project, it did provide a clear indication that customer education is critical. In addition to using the concepts of Design for Six Sigma to focus on customer needs, General Motors must also mold the customer-preconceived perceptions. This can be done through advertising, marketing, and also through the dealer network.

3.3.2 Quality Prediction

Since the CTQ of choice was excessive fuel consumption variation, the relationship between fuel economy and complaints had to be understood. Therefore, only studying comparable full-size trucks (Dodge Ram, Ford F-150, etc.), the advertised composite fuel economy rates were plotted against the J.D. Power and Associates ratings in the excessive fuel consumption category (See Figure 3.2).

![Figure 3.2 J.D. Powers Comparison](image)
This data suggests there is a distinct relationship between the two variables. Using this information and the fact that the current Chevy Silverado achieves a rating of 5.0 problems per hundred (PPH), the goal of 2.0 PPH with 5-sigma\textsuperscript{11} was agreed upon. This goal would create a 60\% reduction in customer complaints. In addition, achievement of 2.0 PPH would likely achieve a rating of best-in-class for the Parallel Hybrid Truck, once in production.

Since the focus of this project was to minimize customer complaints due to fuel economy variation vehicle-to-vehicle, it was critical to identify the variation or standard deviation goal for fuel economy. Based upon the J.D. Powers goal of 2.0 PPH and the fuel economy goals for the Parallel Hybrid Truck Program, a goal for the fuel economy variation was captured with a loss function (See Figure 3.3\textsuperscript{12}). As the standard deviation increases slightly, the J.D. Powers loss increases significantly. The J.D. Powers number can be derived by integrating the J.D. Powers loss function times the probability density function from zero to infinity.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{jd_powers_loss_function.png}
\caption{J.D. Powers Loss Function}
\end{figure}

\textsuperscript{11} 5-sigma was chosen because it was an intermediately value. That is, 4-sigma represents a nuisance item, while 6-sigma represents a safety concern.

\textsuperscript{12} Absolute data considered proprietary.
Although the idea of benchmarking other parallel hybrid vehicles was considered, it was eliminated because of the little value it offered. Unlike the traditional full parallel hybrid vehicles, the GM Parallel Hybrid Truck is only considered to be a “mild” hybrid. That is, the PHT utilizes the hybrid functionality at a minimum. In addition, the Parallel Hybrid Truck would not take advantage of smaller engine architecture, like most typical hybrids. Instead, the Parallel Hybrid Truck would be a low risk introduction of hybrid technology, which would not compromise the functionality and utility of the vehicle for the consumer. Therefore, benchmarking against current full-size trucks provided the most value.

3.3.2. a Hybrid Vehicle Model\textsuperscript{13}

Computer modeling and simulation was used extensively to assist in architecture selection, control strategy development, sub-system design, and component specification for the Parallel Hybrid Truck Program. The Design for Six Sigma project leveraged this already developed simulation tool to complete the necessary design of experiments and optimizations.

The simulation tool used was an internally GM developed program called Overdrive. Overdrive solves systems of ordinary differential equations that approximate the rigid body dynamics of the vehicle. The output from the simulation is a set of parameters that reflect vehicle performance, fuel economy, drive quality, and energy management.

The input to Overdrive is a set of detailed mathematical models that describe the fundamental physics behind the sub-systems that comprise the vehicle. For instance, the engine model includes the basic engine architecture and dimensions, as well as sub-models for the throttle body, manifolds, fueling system, etc. The engine’s fuel conversion efficiency is taken either from the output of an engine simulation or from a dynamometer test. The data is processed and inputted to the engine model as a map of efficiency as a function of speed and load. Similar models represent the transmission sub-system, including gear ratios, shift efficiencies, torque converter characteristics, and shifting schedules.

\textsuperscript{13} Description of the Hybrid Vehicle Model was written by Tony H. Zarger, Development Engineer, at GM Powertrain.
Extensive modifications were made to the conventional vehicle model to accommodate the hybrid architecture. Representations of the electric motor, power electronics, storage devices, and parasitic electrical loads had to be created and integrated into the model. Control strategies for engine cranking, torque smoothing, vehicle creep, and regenerative braking were developed and incorporated to work in concert with the engine control algorithms.

The resulting model of the hybrid architecture and control system closely approximates those of the vehicle. A considerable amount of testing was performed at the component and sub-system level to verify the performance of the model. Because the primary interest was in evaluating the first order system responses for performance, fuel economy, and energy balance, the hybrid vehicle simulation was not designed to model high-frequency transients. To address energy flows due to transient torque smoothing, average torque and power were recorded on instrumented vehicles during dynamic torque smoothing events. The data from these tests were then integrated into the vehicle model. The resulting impact on energy flow and fuel consumption could then be predicted.

By using the previously developed transfer functions and models, the time to complete the Design for Six Sigma project was cut by nearly 3 months. The following modeling strategy was developed for the DFSS project:

![Figure 3.4 Modeling Strategy](image)

Version 17 of the Overdrive PHT specific model was used for the project. Using GM internally support software known as DEXPERT, the experimental protocol was designed. DEXPERT optimized the number of experiments based upon the required output; in addition, the software would output experiment designs, introducing randomness as needed. Simple regression analysis was used to understand the effects of variables. Finally, exploratory experiments would be completed to capture any additional value.
3.3.2.b Structure Diagram

The Design for Six Sigma process focuses heavily on system interactions. Therefore, a structure diagram, mapping out the major system components, was completed. The following seven specific areas were identified as major system contributors to fuel economy gains: engine, transmission, energy storage system, electric machine, controls, power electronics, and vehicle specific. The structure diagram can be viewed in Appendix B.

3.3.2.c Function Diagram

Once the entire system was understood from the structure diagram, the next step was to generate a function diagram. A function diagram describes the activities and the ordered sequence required to accomplish the product’s function. The advantages of creating a function diagram are the following: to establish a common understanding of the product functionality, to define the project boundaries and interfaces, to quantify contributions of various design elements, and to document the elements that require further investigation.

For the Parallel Hybrid Truck, the function diagram was broken down between functions that contributed to fuel economy gains and those that contributed to fuel economy losses. 91 elements were identified in the function diagram. Each of the elements was classified as a) hardware variable, b) controls input, or c) constraint.

![Figure 3.5 Function Diagram](image-url)
A portion of the function diagram can be viewed above (Figure 3.5). The diagram can be interpreted as follows:

Engine off at idle is a function that contributes to PHT fuel economy gain. The fuel economy gain for engine off at idle depends upon the following:

\[(\text{idle fuel consumption rate of the base truck}) \times \text{(engine off time)} \times \text{(frequency of engine off)}\]

The idle fuel consumption rate depends upon the idle engine load and the idle engine speed. And so on.

The entire function diagram can be viewed in Appendix C.

3.3.2.d Variable Reduction

Over ninety elements were identified in the function diagram. Each of the elements was classified as a hardware variable, controls input, or constraint. In addition to the constraints, the individual controls inputs were beyond the scope of the Design for Six Sigma project team. But, in order to capture the effects of the controls variables, two different Parallel Hybrid Truck controls schemes were studied; this provided a quantifiable effect of controls strategy on fuel economy variation. Therefore, from the 91 elements originally identified, only the following 9 hardware variables remained:

- torque converter efficiency
- electric machine/inverter efficiency
- electric machine/inverter current limit
- electric machine/inverter power limit
- battery efficiency or age
- battery voltage limit
- dc/dc converter efficiency
- dc/dc converter current limit
- dc/dc converter power limit

Using engineering judgment, the 3 most significant variables contributing to fuel economy were selected: electric machine/inverter efficiency, battery efficiency or age, and dc/dc converter efficiency. This provided a reasonable experiment size. Using the DEXPERT software tool, a
design of experiment (DOE) was constructed to identify the sensitivity of the three main variables. The following eight run experiment was developed:

Table 3.1 Eight Run DOE Setup

<table>
<thead>
<tr>
<th>RUN 1</th>
<th>Battery Efficiency or Age Factor</th>
<th>DC/DC Converter Efficiency</th>
<th>EM/Inverter Efficiency Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN 2</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>RUN 3</td>
<td>HIGH</td>
<td>LOW</td>
<td>HIGH</td>
</tr>
<tr>
<td>RUN 4</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>RUN 5</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>RUN 6</td>
<td>LOW</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>RUN 7</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>RUN 8</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
</tr>
</tbody>
</table>

3.3.2.e Design of Experiment 1

For the purpose of the first DOE, the battery efficiency was varied between 85 and 95%, the dc/dc converter efficiency was varied between 80 and 90%, and the electric machine/inverter efficiency factor was varied between 0.9 and 1.1. The ranges studied for each variable included the current product specifications and tolerances; this provided the opportunity to verify the current Parallel Hybrid Truck design specifications, in addition to studying the variable sensitivity.

The first design of experiment was completed utilizing control strategy A. Control strategy A is dependent upon the battery state of charge (SOC). Battery state of charge can be viewed simply as the energy level of the battery. If the battery reaches a minimum state of charge as defined by the control algorithm, it will be charged continuously at a relatively low rate until it reaches the maximum state of charge threshold. At that point, charging will end.
For the Parallel Hybrid Truck, the battery state of charge had a significant effect on the fuel economy value. In fact, there is a distinct trade off between battery state of charge and fuel economy. If the final battery SOC is lower than the initial battery SOC, then the energy of the battery was not replaced. In turn, there is a virtual energy gain, and the fuel economy value will appear greater. Therefore, in order to understand the true sensitivity of the variables, the effect of battery SOC had to be eliminated from the fuel economy values. This was completed by repeating each DOE run twice, once at a high initial battery state of charge (0.65) and once at a low initial battery state of charge (0.55). By interpolating or extrapolating the two results, the unbiased fuel economy value could be determined.

### 3.3.2.f Design of Experiment 1 Analysis

Using the transfer function and model developed for the Overdrive software, data was collected for DOE 1. The effect of battery state of charge was eliminated using the interpolation method described previously, and the remaining data was processed using regression analysis (See below).
Table 3.2 Regression DOE 1

<table>
<thead>
<tr>
<th></th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.2303118977</td>
<td>0.020913481</td>
<td>10.746</td>
<td>0.0000</td>
<td>0.18905668</td>
<td>0.271574</td>
</tr>
<tr>
<td>Battery Efficiency * Age</td>
<td>0.2247271015</td>
<td>0.124135587</td>
<td>1.795</td>
<td>0.0751</td>
<td>0.0804746</td>
<td>0.369971</td>
</tr>
<tr>
<td>DC/DC Converter Efficiency</td>
<td>0.561788043</td>
<td>0.020913481</td>
<td>2.6775</td>
<td>0.0076</td>
<td>0.053969</td>
<td>1.1443249</td>
</tr>
<tr>
<td>EM/Inverter Efficiency</td>
<td>0.274212787</td>
<td>0.104906741</td>
<td>2.613871953</td>
<td>0.0501788</td>
<td>-0.0170556</td>
<td>0.5654812</td>
</tr>
</tbody>
</table>

Combined Fuel Economy = (1.31 * Battery Efficiency) + (0.56 * DC/DC Converter Efficiency) + (0.27 * EM/Inverter Efficiency) + \(C\)

From the regression analysis, battery efficiency or age was identified as the major factor affecting the Parallel Hybrid Truck’s fuel economy. The P-value of 0.003 indicated that battery efficiency had less than a 1% chance of being insignificant. Furthermore, the T-statistic of 6.23 indicated that there was little chance the regression coefficient was zero. Therefore, battery efficiency variation would create the greatest amount of fuel economy variation. Tight tolerances on this variable would be critical to maintaining the customer requirements. DC/DC converter efficiency and electric machine/inverter efficiency also proved to be statistically important, although both variables were less influential than the battery efficiency. Finally, using the DEXPERT analysis tools, interaction plots were created (See Appendix D). From these graphs, it was clear that the three variables interacted in some degree, although it seemed fairly moderate. The results of the Design of Experiment 1 analysis were consistent with the expected results.

3.3.2.g Design of Experiment 1 “Real World” Analysis

In order to understand the relationship between the Design of Experiment results and the Design for Six Sigma customer goals, a real world analysis was completed. Since the average customer will realize the effects of battery state of charge, the effects of SOC on fuel economy must be considered. Therefore, all the trials, both starting at a high and low battery SOC, were included for the analysis; that created a total of 16 various data points with variable battery state of charge, battery efficiency, dc/dc converter efficiency, and electric machine/inverter efficiency.

Based upon J.D. Powers loss function, for the given average of the sixteen data points, a standard deviation of 0.36 needed to be met to achieve the goal of 2.0 PPH for excessive fuel consumption. For DOE 1, the standard deviation achieved was 0.27, thereby surpassing the goal of 2.0 PPH. The goal of 5.00 sigma was exceeded; in fact, 5.33 sigma is predicted for fuel economy variation. The fact that the simulation only considers the standard FTP driving cycle is a valid concern, but for the basis of the Design for Six Sigma project, this analysis was as “real
world” as possible. Therefore, for the given product specifications studied, the design for the Parallel Hybrid Truck utilizing control strategy A is considered robust in the consumer’s eyes.

3.3.2.h State of Charge Analysis

In an effort to quantify the effect of battery state of charge on fuel economy, regression analysis was completed using delta state of charge (final state of charge – initial state of charge) as an additional variable; both a city cycle and highway cycle delta SOC were considered. Interestingly, the regression analysis indicated that city cycle delta state of charge was the most important factor influencing combined fuel economy. Not only did the P-value indicate a near 100% chance of city cycle delta SOC being significant, but also the regression coefficient for city cycle delta SOC was nearly 5 times larger than that for battery efficiency.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.793437518</td>
<td>25.904329</td>
<td>1.69E-10</td>
<td>0.39936967</td>
<td>2.108652709</td>
</tr>
<tr>
<td>Battery Efficiency at Age</td>
<td>0.388952939</td>
<td>2.132277</td>
<td>0.0495016</td>
<td>0.3753701</td>
<td>2.108652709</td>
</tr>
<tr>
<td>D/C Converter Efficiency</td>
<td>0.297890206</td>
<td>0.168263</td>
<td>0.0108651</td>
<td>0.1068507</td>
<td>0.19884366</td>
</tr>
<tr>
<td>EM/Inverter Efficiency</td>
<td>-0.450738457</td>
<td>-1.899892</td>
<td>0.0613592</td>
<td>-0.903952</td>
<td>1.9986945</td>
</tr>
<tr>
<td>City Cycle Delta SOC</td>
<td>0.3097393188</td>
<td>0.170464</td>
<td>0.0495016</td>
<td>0.1068507</td>
<td>0.48615899</td>
</tr>
<tr>
<td>Highway Cycle Delta SOC</td>
<td>0.430015689</td>
<td>0.2933483139</td>
<td>0.0495016</td>
<td>0.1068507</td>
<td>0.48615899</td>
</tr>
</tbody>
</table>

Combined Fuel Economy = (5.51 * City Delta SOC) + (1.24 * Battery Efficiency) + C

Therefore, maintaining a minimal delta state of charge during conditions of heavy hybrid loading, such as driving in the city, is critical to achieving relatively high fuel economies. The customer will average out the effect of battery state of charge on fuel economy, as the vehicle is operated repeatedly. In other words, this effect will be masked to the customer. It is only an issue when instantaneous fuel economy is considered, such in the case of vehicle fuel economy certification. Certification is a one-time test, and the option of averaging the effects of battery SOC is not valid. Therefore, the control strategy algorithm must anticipate and account for this issue accordingly.

3.3.2.i Design of Experiment 2

The second design of experiment was constructed in the same manner as the first, with one exception- the controls strategy differed.
Control strategy B increases the range of acceptable battery state of charge. Therefore, the battery can reach a much lower energy level, but it will compensate by charging at a faster rate to a higher threshold. Since control strategy B puts a greater load and emphasis on the battery, it is expected that the battery efficiency will have an even greater significance than in control strategy A.

3.3.2.j Design of Experiment 2 Analysis

With control strategy B, regression analysis indicated that all the variables studied were statistically significant. All of the variables have less than a 5% chance of being insignificant. Much like the first design of experiment though, the most significant variable was battery efficiency. This is consistent with the expected results.

Table 3.4 Regression DOE 2

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.217945488</td>
<td>88.9023239</td>
<td>9.1772E-08</td>
<td>0.87526258</td>
<td>1.78107471</td>
</tr>
<tr>
<td>Battery Efficiency or Age</td>
<td>1.328156485</td>
<td>0.163128847</td>
<td>8.1417573</td>
<td>0.00123827</td>
<td>0.155280577</td>
</tr>
<tr>
<td>DC/DC Converter Efficiency</td>
<td>0.0082003285</td>
<td>0.163128847</td>
<td>3.7283424</td>
<td>0.02023262</td>
<td>0.01565378</td>
</tr>
<tr>
<td>EM/Inverter Efficiency</td>
<td>0.329205977</td>
<td>0.081564424</td>
<td>4.0361467</td>
<td>0.01565378</td>
<td>0.10274364</td>
</tr>
</tbody>
</table>

Combined Fuel Economy = (1.32 * Battery Efficiency) + (0.61 * DC/DC Converter Efficiency) + (0.33 * EM/Inverter Efficiency) + C
3.3.2. k Design of Experiment 2 “Real World” Analysis

For the given average of the sixteen data points, the J.D. Powers loss function indicated a standard deviation of 0.36 needed to be met to achieve the project goals. For DOE 2, a standard deviation of 0.27 was achieved; 5.34 sigma is predicted for fuel economy variation, exceeding the goal of 5.00 sigma. Therefore, with the given product specifications under control strategy B, the Parallel Hybrid Truck would be robust according to the consumer.

In addition to the greater sensitivity of all the variables in control strategy B, control strategy B had other effects on the outputs. Interestingly, the mean of the fuel economy for the real world analysis proved to be greater with control strategy B than with control strategy A. In contrast though, with control strategy B, the actual variation was greater than with control strategy A. This demonstrates the trade-off between a higher mean fuel economy and a less varied fuel economy. It is important to understand the statistical importance of this data and how it correlates to the goals of the project. Although control strategy A achieved less fuel economy variation than control strategy B, when using the Design for Six Sigma statistical process, control strategy B would be recommended over control strategy A because it provided a greater sigma. This indicated that control strategy B could more consistently provide the customer required fuel economies.

3.3.3 Optimization

Since the Design for Six Sigma Process proved the current product specifications were robust, in order to add more value to the project, the minimum limits for each variable were determined. This was an effort to move towards the optimized result.

By holding two of the variables at their worst-case condition, the third variable was repeatedly lowered until the output of the fuel economy reached the minimum limit. For example, the dc/dc converter efficiency was held at 80%; the electric machine/inverter efficiency factor was held at 0.9; then, the battery efficiency was continually lowered until the combined fuel economy reached the minimum limit.
The resulting minimum variable efficiency was calculated using double interpolation. That is, the first result was obtained by interpolation. The model was then run with the first interpolated result; this new result provided a point for a second interpolation. Using this technique provided a more exact minimum efficiency.

<table>
<thead>
<tr>
<th>Battery Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC/DC Converter Efficiency</td>
</tr>
<tr>
<td>75%</td>
</tr>
<tr>
<td>EM/Inverter Efficiency Factor</td>
</tr>
<tr>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 3.5 Optimization Results

At first glance, these above results may appear unrealistic. But, it is important to remember that these are the minimum efficiencies, with a zero percent standard deviation. If the battery could be manufactured exactly at 75% efficiency and the other current product specifications remained, the entire Parallel Hybrid Truck system would meet the consumer product requirements. In many production environments though, perfect manufacturing with zero percent deviation is nearly impossible. Therefore, this analysis just provides a baseline of minimum efficiencies.

In addition to the manufacturability and repeatability concerns, the other issue is this analysis accounts only for independent changes to efficiencies; or, the minimum efficiency limits were determined by independently changing one of the variables. Finally, with the current model and simulation, additional loads to the Parallel Hybrid Truck system, such as air conditioning, could not be accounted for. Additional energy loads on the system may degrade the system performance, both fuel economy rates and fuel economy variation, thereby requiring higher efficiencies than initially calculated.

Therefore, while this analysis does provide a baseline for the main variable efficiency limits, it by no means indicates that the Parallel Hybrid Truck Program should lower the variable efficiencies to these values. Instead, this analysis provides directionally correct recommendations for adding more value to the project. By decreasing variable efficiencies, cost
can be reduced, and more value can be captured without compromising the customer’s true needs.

3.3.4 Test & Verify

In the final phase of the Design for Six Sigma Process, a pilot build should be completed to confirm the DFSS model; this in turn, confirms the results of the DFSS project predictions. Since the model was already confirmed with pilot Parallel Hybrid Truck builds, this step was unnecessary for this specific DFSS project. Therefore, the final step was to capture and document the results.

One method used to summarize the project results and to provide a quantitative risk assessment is through the Design for Six Sigma scorecard. Typically the scorecard is part of the standardized work incorporated in DFSS. It is a format for consistent presentation of data, which is very structured and prioritized.

Typically, a spreadsheet format is utilized for the Design for Six Sigma Scorecard. This allows automatic calculation of the six sigma specifications and statistics. Inputs into the scorecard are typically specifications, means, and standard deviations for the system and subsystems. Using this information, the defects per unit (DPU), defects per million opportunities (DPMO), and sigma can be calculated.
For the Parallel Hybrid Truck Design for Six Sigma project, the top level scorecard looked as follows:

Table 3.6 Top Level Scorecard

<table>
<thead>
<tr>
<th>Assembly Name</th>
<th>Supplied Parts</th>
<th>Mfg &amp; Asm</th>
<th>Performance</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHT Fuel Economy Variation</td>
<td></td>
<td></td>
<td>7.544E-03</td>
<td></td>
</tr>
<tr>
<td>Energy Storage System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total DPU</td>
<td></td>
<td></td>
<td>7.889E-03</td>
<td></td>
</tr>
<tr>
<td>Total Opportunities</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$Z_{ST}$</td>
<td></td>
<td></td>
<td>4.52</td>
<td></td>
</tr>
</tbody>
</table>

Scorecard DPU: 7.889E-03
Scorecard Opportunities: 6
Scorecard $Z_{ST}$: 4.52

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For each major system contributing to the fuel economy variation, a specific scorecard also existed; all systems had a very similar scorecard setup. The following was the scorecard for the Electric Machine System:

Table 3.7 Subsystem Worksheet

<table>
<thead>
<tr>
<th>Performance Worksheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly Description:</td>
</tr>
<tr>
<td>Analyst:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Lower Spec</th>
<th>Upper Spec</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Short or Long</th>
<th>dpmo</th>
<th># of Times Applied</th>
<th>VSM AS Model</th>
<th>DPU</th>
<th>$Z_{ST}$</th>
<th>$Z_{Target}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM Efficiency Factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Finally, the following system scorecard existed, which captured results from the design of experiments:

Table 3.8 System Scorecard

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Lower Spec</th>
<th>Upper Spec</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Short or Long</th>
<th>dpnm</th>
<th># of Times Applied</th>
<th>DPU</th>
<th>Zst</th>
<th>Ztarget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advertised fuel economy (city) (mpg)</td>
<td>City Base</td>
<td>PHT City</td>
<td>P-H City</td>
<td>S</td>
<td>1</td>
<td>7.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advertised fuel economy (Highway) (mpg)</td>
<td>Hwy Base</td>
<td>PHT Hwy</td>
<td>PHT Hwy</td>
<td>S</td>
<td>1</td>
<td>3.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined (mpg)</td>
<td>Combined</td>
<td>PHT Combined</td>
<td>PHT Combined</td>
<td>S</td>
<td>1</td>
<td>5.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Control Strategy A

Vehicle-to-Vehicle FE Variation

Combined with full variation (mpg) | Combined | PHT A Combined | PHT A Combined | S | 1 | 5.33 | 5.0 |

Target Standard Deviation

Control Strategy B

Vehicle-to-Vehicle FE Variation

Combined with full variation (mpg) | Combined | PHT B Combined | PHT B Combined | S | 1 | 5.34 | 5.0 |

Target Standard Deviation

Upon completion of the project, all project information (including the scorecards) was posted to the General Motors intranet, where DFSS projects are actively shared across the organization.

3.3.5 Organizational Aspects of the Project

In an effort to maintain the standardized structure of the Design for Six Sigma Process, General Motors created DFSS support teams within each organization. Within GM Powertrain, an executive role titled Process Guardian was created to maintain, propagate, and employ the principles of Design for Six Sigma. Both DFSS coaches and mentors report to the Process Guardian.

A Design for Six Sigma coach is assigned to each project team, and he or she typically becomes an integral member of the project team. Coaches are Six Sigma Black Belts with a variety of project experience and strong technical backgrounds. On the other hand, Design for Six Sigma mentors are trained as Master Black Belts. Typically, a coach becomes a mentor after completing a significant number of projects and additional training. Not only are mentors responsible for Design for Six Sigma project reviews, but they also provide value insight and significant input into a project’s direction.
At General Motors, Design for Six Sigma teams consist of the following roles and responsibilities:

<table>
<thead>
<tr>
<th>Position</th>
<th>Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFSS Team Leader</td>
<td>Run DFSS Meetings</td>
</tr>
<tr>
<td></td>
<td>Maintain scorecards, metrics</td>
</tr>
<tr>
<td></td>
<td>Report out at all DFSS Tech. Reviews</td>
</tr>
<tr>
<td>DRE(s)/Technical Specialists</td>
<td>CTQ rolloff/rollup</td>
</tr>
<tr>
<td></td>
<td>Structural Diagram</td>
</tr>
<tr>
<td></td>
<td>Functional Flow Diagram</td>
</tr>
<tr>
<td></td>
<td>Create transfer functions</td>
</tr>
<tr>
<td></td>
<td>Provide design data</td>
</tr>
<tr>
<td></td>
<td>Assignments in area of expertise</td>
</tr>
<tr>
<td>VSAS</td>
<td>System models</td>
</tr>
<tr>
<td></td>
<td>Create &amp; exercise math models</td>
</tr>
<tr>
<td>Quality</td>
<td>Quality data from plant, supplier, etc.</td>
</tr>
<tr>
<td></td>
<td>Gage R &amp; R, process capability</td>
</tr>
<tr>
<td>Mfg.</td>
<td>Manufacturing data, expertise</td>
</tr>
<tr>
<td></td>
<td>BOP expertise</td>
</tr>
<tr>
<td>Reliability</td>
<td>Statistical expertise</td>
</tr>
<tr>
<td></td>
<td>DoE, reliability tools</td>
</tr>
<tr>
<td>Coach</td>
<td>Coach the Team Leader</td>
</tr>
<tr>
<td></td>
<td>Train the team</td>
</tr>
<tr>
<td></td>
<td>Assist in team start up</td>
</tr>
<tr>
<td></td>
<td>Attend DFSS team meetings</td>
</tr>
<tr>
<td></td>
<td>Attend all DFSS technical reviews</td>
</tr>
</tbody>
</table>

Typically, the Design for Six Sigma team leader is an Assistant Chief Engineer or someone at a similar technical level for the related project; often the team leader initiates the project idea. Design release engineers (DREs), who are responsible for a specific part or subsystem’s design specifications and functions, and other technical specialists provide specific expertise. Having DREs as integral members of the DFSS team provides a two-fold benefit. For instance, design release engineers can provide critical data and in-depth subsystem understanding to the Design for Six Sigma team. In return, the Design for Six Sigma team provides the DREs the statistical support for making good design decisions; instead of making decisions based upon previous experience or intuition, design release engineers can make better decisions based upon the Six Sigma fundamental philosophies and the customer needs.

Vehicle Synthesis Analysis and Simulation or VSAS provides math modeling skills and techniques to the team. A representative from the quality organization provides data from suppliers and also process capabilities. Depending upon the specific Design for Six Sigma project, a representative for manufacturing may be assigned to the team; typically, he or she
provides bill of process and manufacturing expertise. Finally, a representative from the reliability network provides the necessary statistical and design of experiment expertise to complete the Design for Six Sigma project.

Each Design for Six Sigma project is required to complete team training (2 days) and a team project kick-off meeting; in addition, three project technical reviews must be completed. Typically, the first technical review occurs at the end of the Critical to Quality (CTQ) phase. The second technical review occurs near the end of the Quality Prediction phase. And, the third or final technical review occurs upon completion; it is often a project closure meeting, and the Process Guardian must attend the meeting in addition to the team, coach, and mentors.
Chapter 4   Elements of a Successful Design for Six Sigma Organization

In order for a firm to be successful with Design for Six Sigma implementation, both cultural and technical successes need to be achieved. George Eckes, founder and principal consultant for Eckes & Associates, Inc. a company specialized in Six Sigma implementation, quantifies the success of a Six Sigma organization by the following formula:

\[ Q \times A = E \]

E refers to the extent that a company achieves Six Sigma as a technical measure of performance. Q, or quality, is a measure of the strategic and tactical elements of the Six Sigma initiative. A, or acceptance, measures the cultural acceptance of the strategic and tactical elements.

4.1 Cultural Elements\(^\text{14}\)

Many believe that “implementing the hard tools (technical) of Six Sigma is easy, while implementing the easy tools (cultural) is hard”. In fact, most firms often fail because they do not gain the full acceptance of the Six Sigma culture.

During Eckes consulting work with firms such as GE Capital, Pfizer, Westin, Honeywell, and Volvo, he found the following reasons why change has been successful in an organization: strong leadership (78% of the time), need for change communicated (59%), clear and motivation goals or objectives (56%), resistance was managed (44%), and the culture was modified to encourage change (38%). Interestingly, the reasons why change has been unsuccessful are very similar; these reasons include the following: lack of clear goals (87% of the time), need for change was never understood (79%), no or poor leadership (46%), those against the change were allowed to win (40%), and there was no incentive to change (32%).

\(^{14}\) This section is derived from George Eckes book Making Six Sigma Last: Managing the Balance Between Cultural and Technical Change.
Eckes recommends the following six steps to create and improve acceptance of the Six Sigma culture:

1. Create the need for Six Sigma
2. Shape a vision of Six Sigma so that employees understand the desired results and new behaviors of the Six Sigma organization
3. Mobilize commitment to Six Sigma and overcome resistance
4. Change your systems and structures to support the new Six Sigma culture
5. Measure Six Sigma cultural acceptance
6. Develop Six Sigma leadership

4.1.1 Creating the Need for Six Sigma
In order for an organization to emphatically embrace Design for Six Sigma, employees at all levels of the firm must see the need for the change. There are two primary methods to motivate people to change—threat and opportunity. People tend to be motivated to change when they are confronted by a real or perceived threat, such as layoffs or the idea that competitors are improving through the use of Design for Six Sigma. Also, people can be motivated to change through real or perceived opportunity, such as improved profitability. While threats are a short-term method of motivation, opportunities tend to be more long-term.

While it is suggested that a firm both leverage threats and opportunities as a means to motivate change, they need to be well thought out in advance. Both should be used sparingly. In addition, a firm should be in the position to prove a threat or opportunity if needed; otherwise, credibility of the management could be compromised.

4.1.2 Shaping a Clear Six Sigma Vision
That which is not understood is resisted, therefore it is critical to shape a vision which is clear and understood by all. Typically, the vision of the Six Sigma culture includes the following concepts: improvement, data, facts, process, customers, employees, analysis, measurement, projects, perfection, never-ending, and defects. Using these fundamental concepts coupled with
any corporate specific ideas for Design for Six Sigma, a Six Sigma mission should be created. In addition, the organization needs to develop goals and acceptable behaviors for the Six Sigma culture.

4.1.3 Committing to Six Sigma

Since the universal reaction to change is loss, resistance to a newly implemented Design for Six Sigma philosophy should be expected. There are four main types of resistance: technical when Six Sigma produces feelings of inadequacy in the stakeholder, political when the stakeholder perceives Six Sigma as a loss, organizational when the stakeholder experiences issues of control, pride, or loss of ownership over Six Sigma, and finally individual when stakeholders experience fear. In order to combat resistance, first the stakeholders must be identified. Next, the specific type of resistance should be identified, and the appropriate strategy such as education, information, or involvement should be used. Finally, though, and most importantly, the corporation must signal its commitment to the process with every action. Whether it is to devote a significant budget to Six Sigma training and consultants, to measure employees actively on their involvement with Six Sigma activities, or to simply have top leadership campaign for Six Sigma, a company must send a clear signal to all employees that they are sincerely committed to the Six Sigma efforts.

4.1.4 Changing Systems for Support of Six Sigma

In order to demonstrate full organization support of Design for Six Sigma, it is important to change internal systems the support the new cultural change. Creating a Six Sigma infrastructure is critical to the success of organization’s mission and goals. Eckes recommends addressing the following six systems and structures in order to get maximum impact: hire Six Sigma people into the organization, develop Six Sigma people in the organization, evaluate Six Sigma behaviors, reward and recognize Six Sigma behaviors, communicate Six Sigma to the organization, and change job structures to strategically match the Six Sigma objectives.

Hiring Six Sigma talent into the organization is an important aspect to changing the current organization systems. Not only will the Six Sigma talent provide instantaneous adoption to the Design for Six Sigma culture and behaviors, but these individuals also fulfill the need for a Six
Sigma role model to the entire organization. In addition, by hiring Six Sigma talent, firms tend to attract more Six Sigma talent. This establishes a recurring loop in which a firm attracts individuals based upon the organizations culture; in turn, by attracting Six Sigma talent, the organization reinforces the Six Sigma culture it is trying to adopt. This is a critical cycle which can make the successful transformation to Six Sigma far more probable.

In addition to hiring Six Sigma talent in the organization, people currently within the organization need to be developed. This can be accomplished best through ongoing training. It is suggested that organizations offer at least the following types of courses: Six Sigma overview, Green Belt training for champions and project leaders, and Black Belt training for advanced participants. In addition to training, job structures need to be changed or created to match the Six Sigma goals. The key positions suggested to support the Six Sigma culture include a quality leader (executive leadership), master black belts (technical leaders), black belts (project coaches), and green belts (champions and project leaders).

Finally, reward and recognition can be used to supplement the transformation of the organization’s system and structure. By evaluating the individual contribution of employees during specific projects with fairness and balance, organizations can provide bonuses and other forms of recognition to both individuals and supporters. This can also be leveraged as a means to communicate Six Sigma successes to the rest of the organization. Newsletters or the intranet could be used not only to publicize the recognition, but they could also be used to publicly demonstrate support for the Six Sigma culture to the entire firm.

4.1.5 Measuring Cultural Acceptance

Consistent with the Six Sigma process, one cannot improve anything unless it is measured. Therefore, if a company chooses to implement Six Sigma philosophy, it should be consistent and measure the cultural acceptance of the effort. Eckes recommends the following measurement technique:

For Q, Quality, measure business process management, training, consulting, project management, and infrastructure on a scale of 0 to 5, with 5 being high.
For A, Acceptance, measure creating need, shaping vision, mobilizing commitment, measuring acceptance, systems/structures, and leadership support on a scale of 0 to 5, with 5 being high. Based on the Likert Scale, in which Likert found that a 1-5 scale is more mathematically accurate than a 1-10 scale, multiply each of the results by 2. From the Q or Quality measures, determine the overall average. Likewise, from the A or Acceptance measures, determine the overall average. Compute E, the measure of cultural effort success, by multiplying the overall quality average by the overall acceptance average. The following scale indicates an interpretation of the E measure:

<table>
<thead>
<tr>
<th>QxA=E Score</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 20</td>
<td>Wasted their money on Six Sigma</td>
</tr>
<tr>
<td>21 – 40</td>
<td>Some tactical results, initiative will likely die</td>
</tr>
<tr>
<td>41 – 60</td>
<td>Significant tactical results, initiative will focus on projects for life of Six Sigma</td>
</tr>
<tr>
<td>61 – 80</td>
<td>Cultural transformation, but may take some time</td>
</tr>
<tr>
<td>81 – 100</td>
<td>Cultural transformation, a world-class Six Sigma organization</td>
</tr>
</tbody>
</table>

It is important to remember that Eckes $E = Q \times A$ is just one method of measuring cultural transformation for a Six Sigma corporation. But, it does provide some information and feedback to the organization. From Eckes experience, only about 30% of firms have achieved a cultural transformation, 50% have achieved a tactical return on investment, and 20% have completely wasted their money on Six Sigma efforts.

4.1.6 Developing Six Sigma Leadership
As with any key corporate initiative, leadership must be developed to embody its principles. For Six Sigma leadership, one must realize that Six Sigma itself is more than just an initiative; it is a
management philosophy. Six Sigma leaders, like the procedure, need to be committed to process, not just function, and make decisions based on fact and data instead of inherent management skills. Six Sigma leaders also need to understand both the technical and strategic elements of the philosophy.

4.2 Technical Elements
Since decisions in a Six Sigma organization are data driven, it is important that all employees understand basic statistical analysis. In addition, employees directly involved with the Design for Six Sigma efforts should understand DFSS specific statistics and advanced analysis tools.

4.2.1 Sigma Determination
The basic DFSS measurement is sigma itself. The following schematic illustrates how sigma can be determined:

![Figure 4.1 Sigma Determination](image)

As discussed in Chapter 2, first the critical to quality (CTQ) characteristics must be identified. Based upon the CTQ customer requirements, the number of defects per unit (DPU) must be defined. Also, the number of opportunities that a defect may occur needs to be defined; opportunities can occur at any step in the process where the defect could arise for a given CTQ. From that information, the defects per opportunity (DPO) can be calculated by dividing the DPU value by the number of opportunities. By multiplying the DPO by 1 million, the defects per million opportunities (DPMO) can be determined. Finally, using a sigma table, the DPMO can be converted to a sigma value. Defect per unit, defect per million opportunities, and sigma are the standard Six Sigma measurements, while defect per unit is an intermediate measurement to simplify calculations.
4.2.2 Advanced Analysis Tools\textsuperscript{15}

There are a number of common advanced Six Sigma analysis tools worthy of discussion. The most widely used are the following:

- **Statistical Significance Tests**
  Chi-square, t-test, and ANOVA are the most widely used statistical significance tests. Use of these tools allow Design for Six Sigma teams to confirm a problem or meaningful change, check validity of data, determine a pattern or distribution, or validate or disprove a hypothesis.

- **Correlation and Regression**
  Both correlation and regression are important to identify relationships between various variables or inputs and outputs.

- **Design of Experiments (DOE)**
  Design of experiments is a method used for testing and optimizing the performance of a design. Using DOEs, a plan can be developed to gather empirical observations about variables through experimentation.

- **Failure Mode and Effects Analysis (FMEA)**
  FMEA is a set of guidelines, a process, and a form to identify and prioritize potential problems or failures. Coupled with the concept of voice of the customer, FMEA could be used to identify potential Design for Six Sigma projects, and it could also be used to identify critical design parameters that may affect the outcome of the DFSS project.

Many of these tools can become complex and confusing; therefore it is critical to provide in-depth training and support. Without the proper utilization, these tools will not provide the maximum value to Design for Six Sigma projects.

\textsuperscript{15} Additional reading on advanced analysis tools can be found in Chapter 18 of *The Six Sigma Way: How GE, Motorola, and Other Top Companies Are Honing Their Performance*. 

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Chapter 5  Is Design for Six Sigma Right for the Automotive Industry?

Although Design for Six Sigma has taken the automotive industry by storm over the past few years, Six Sigma is not synonymous with success. Design for Six Sigma and the Six Sigma philosophies can add value to the industry, but like any strategy or tool, it can only be successful if it is used properly and the corporate infrastructure supports it.

5.1 Advantages

There are several advantages for Design for Six Sigma in the automotive industry. First, it is a fact that Design for Six Sigma and Six Sigma philosophies have added tremendous value to other, somewhat stagnant industries. Motorola is the best example for the automotive industry; like the automotive industry currently, at the time Motorola implemented Six Sigma techniques, Motorola was losing market share to a higher quality foreign manufacturers. Therefore, use of Six Sigma techniques in general may give the US automakers the quality advantage needed to gain increased market share.

Design for Six Sigma specifically focuses on listening to the customer requirements and needs. This is an important function for any engineering and manufacturing firm to acquire; it not only prevents over-engineering in general, but it also focuses employees on the truly important product characteristics. Therefore, DFSS creates a greater motivation for the automotive industry to accurately understand the consumer’s needs and purchasing decisions. The underlying motivation can be either quality-driven, financially-driven, or both. But, for the first time in the automotive industry, there is a clear, strong, financial tie to customer approval that can be used as early as the research phase of design.

In the automotive industry where companies are “large” and rely on policies and procedures, Design for Six Sigma provides an advantage with its rigorous, standardized process. It is consistent with most automotive companies’ current business characteristics. Therefore, it reinforces the current standardization techniques, as it creates a framework to make data-based design decisions. With most large automotive firms focusing more on component knowledge and less on architectural knowledge, Design for Six Sigma fits well, as engineers can individually contribute significantly to the process.
Design for Six Sigma also offers a marketing advantage to many automotive companies. Investors and potential customers may view the efforts as a quality advantage if they are promoted accordingly. This in turn can result in increased profitability and perceived value. In fact, Lipper Analytical is on record as saying that 20 percent of General Electric’s stock price was due to GE’s reputation for practicing Six Sigma (Eckes 29). Many of the automakers should be able to leverage Six Sigma similarly to GE to capture the same gains.

5.2 Disadvantages

While there are many advantages to adopting Design for Six Sigma and the Six Sigma philosophies, there are also a number of disadvantages for the automotive industry. First, Six Sigma is not an automatic cure for an ailing business. For example, GE Appliances has been struggling with poor performance for several years; it has found that Six Sigma has taken longer to deliver on the needed turnaround than had been hoped (“Repairman”). Therefore, it is important for the automotive industry to realize this fact and sell the process to employees realistically.

Design for Six Sigma as a performance-improvement initiative can boost operating results, only if it is positioned and integrated properly. But, within the automotive industry, there are a number of improvement efforts that fall under the umbrella of each company’s individualized manufacturing system or strategy—ideas such as design for manufacturability, design for assembly, robust engineering, and etc. Often, these independent improvement efforts are disconnected. Therefore, without the interoperability and linking, the proliferation of improvement efforts creates a risk for the success of Design for Six Sigma in the automotive industry. Furthermore, with the self-reinforcing nature of automotive organizations, making a minor adjustment to the current manufacturing system or strategy by adding Design for Six Sigma may actually decrease the performance of the firm while bringing it no closer to the desired new state (Henderson).

In addition to the linking between improvement efforts, linking between the various design groups needs to occur within the automotive industry. Currently, this is a significant barrier to
the success of adopting Design for Six Sigma, and the result is sub optimization, which often is diffused as the design process continues. For instance, with the case study presented in Chapter 3, the DFSS project was specifically tied to powertrain optimization based upon customer requirements. If those same customer requirements and goals are not carried to the next step in the design process, vehicle integration and design, the efforts of the powertrain Design for Six Sigma team will be diluted. With the current structure of organizations within the automotive industry, the organizational linking required for the success of DFSS may be a significant issue. A universal awareness of the process and metrics needs to be created, in order to hold everyone accountable and to eliminate sub optimization.

The final issue for implementation of Design for Six Sigma and Six Sigma philosophies within the automotive industry deals with disruption of technology. Within the next ten years, automotive manufacturers plan to introduce alternative powered vehicles such as fuel cells, full hybrids, etc. to the market; many expect this to create a major technological disruption to the automotive industry in general. This disruption can be captured in a technological S-curve (Figure 5.1).

![Figure 5.1 Technology S-curve](image)

An S-curve portrays an industry life cycle, plotting performance rate versus time. The current internal combustion engine powered vehicle is in the maturity phase of the first S-curve. With a
disruption to fuel cell vehicles, the industry would move to the ferment phase on a secondary S-curve (dashed line).

Disruptive innovations always require a major change in business practice from that of existing technologies; typically companies need to move towards a more entrepreneurial-type environment. With that in mind, there is some cause for concern over implementing a rigorous, standardized process such as Design for Six Sigma.

Firms attempting to grow through innovation need to balance the entrepreneurial drive or ability to do things differently with the need to coordinate efforts with the existing business (Figure 5.2).

![Diagram](image)

*Figure 5.2 Managing Control & Coordination (Henderson)*

By implementing Design for Six Sigma, automotive companies will be increasing their value on the control and coordination axis. In turn, this will make it more difficult to maintain a balance between entrepreneurial drive and control; also, automakers may be moving further away from the ideal balance. While typically in a mature industry this does not present as much of an issue, when dealing with disruptive technologies, standardized processes such as DFSS may actually hinder innovation instead of stimulating it.
Chapter 6  Conclusions

Overall, Design for Six Sigma and the Six Sigma philosophies seem to have made their “kick” into the automotive industry. But, the automotive industry cannot expect to jump on the Six Sigma bandwagon and find a panacea. Instead, implementing Design for Six Sigma requires active change management, which may currently be lacking.

6.1 Insights

While it is not very surprising, each company successful at implementing Six Sigma philosophies had a very supportive, almost evangelical CEO. Most well known for his support of Six Sigma, Jack Welch of GE titled his 1997 Key Annual Meeting speech “A Learning Company and Its Quest for Six Sigma”. At every opportunity available, Welch publicly and actively demonstrated his support for the Six Sigma way of business. Not only does he convey his true commitment in the process, but he also ties it into the financial success of the business very well. Currently within the US automotive industry, CEO’s with strong biases for Six Sigma do not appear to exist. Without that leadership, the automotive employees may interpret DFSS as a “flavor of the month” strategy instead of the revolutionary process it can be.

Therefore, the CEO’s understanding and commitment is critical to acceptance of Design for Six Sigma and its philosophies into the corporate culture. Beyond the technical education and learning tied to Six Sigma, automotive companies must also achieve a cultural transformation to capture the maximum return on investment and value from Six Sigma. The key cultural ideas are the following:

1. Create the need for Six Sigma
2. Shape a vision of Six Sigma so that employees understand the desired results and new behaviors of the Six Sigma organization
3. Mobilize commitment to Six Sigma and overcome resistance
4. Change your systems and structures to support the new Six Sigma culture
5. Measure Six Sigma cultural acceptance
6. Develop Six Sigma leadership
Design for Six Sigma does offer additional value to the automotive industry though. As demonstrated from the case study completed for the GM Parallel Hybrid Truck, “fuzzy” customer complaints were easily transformed into specific product specifications by using the DFSS standardized process; this was a tremendous insight that converted those somewhat skeptical of the process into true believers. In addition, the product design was proven statistically robust, focusing the organization and team on data-driven design decisions. Furthermore, Design for Six Sigma offered the opportunity to better understand the customer, gain more market share, increase quality, prevent over-engineering, and improve marketability and profitability.

In contrast though, DFSS is not a cure-all for the automotive industry. Therefore, it must be promoted to employees and users realistically. In order for Design for Six Sigma to be successful, the process must be integrated with current improvement efforts and across organizational functions. In the current automotive industry with the vast majority of improvement efforts, the goals of Design for Six Sigma are likely to be convoluted with contradictory goals such as “boundaryless” or “speed”. The juggling act to manage all of these improvement efforts by the automotive companies will be arduous to say the least.

Finally, DFSS may hinder some of the innovation required to deal with emerging disruptive technologies. Therefore, it is important to maintain a fine balance between entrepreneurial drive and control and coordination, while implementing the Design for Six Sigma standardized process. Leveraging the Design for Six Sigma process more as a flexible system that encompasses many tools, concepts, and principles is important to achieving the maximum value from the process.

6.2 Recommendations for Future Work
With regard to the present work for the General Motors Parallel Hybrid Truck (PHT) program, future projects should be chosen based upon potential impact. For instance, the high value Design for Six Sigma projects for the PHT include the following: maximizing fuel economy, minimizing PHT feature cost to the consumer, minimizing the effect of driving pattern on fuel economy, or reducing hybrid operating sensations to the consumer. In general, it is
recommended that General Motors develop a system to select Design for Six Sigma projects based upon the corporation's goals and needs; this not only focuses and utilizes employees on the critical projects, but it also demonstrates the commitment of the corporation to data-driven decision making.

In general, the automotive industry's infrastructure creates a number of challenges to successful implementation of Design for Six Sigma. First, with the disjointed Product Engineering and Manufacturing Engineering organizations, the industry currently cannot experience the full benefit from DFSS projects. With all of the Design for Six Sigma projects originating in Product Engineering currently, the Manufacturing Engineering organization currently does not "buy-in" to the project goals. Although it is recommended that at least one manufacturing engineer participate as a member of a Design for Six Sigma team, this does not alleviate the "buy-in" issue because often the insights of the manufacturing engineer are not leveraged. Therefore, some type of linking needs to be created between the Manufacturing Engineering and Product Engineering organizations at a level consistent with Design for Six Sigma projects. Like the Process Guardian position for DFSS in Product Engineering, a counterpart Process Guardian should exist in Manufacturing Engineering.

In addition, Design for Six Sigma projects should be encouraged from the Manufacturing Engineering organization. Manufacturing engineers experience the product design issues on a daily basis; this creates a strong motivation for manufacturing engineers to solve product design problems- instantaneous "buy-in". Leveraging the already incorporated principle of continuous improvement, which has existed within the automotive industry for some time now, manufacturing driven DFSS projects provide the opportunity to address re-engineering efforts most effectively.

The last infrastructure issue deals with the product design cycle. With the current process for example, the Powertrain group would design the engine and transmission for a vehicle and then pass the design to the Vehicle Integration group, who is responsible for integrating the powertrain design with the vehicle/body design. Often, designers from the Powertrain group and Vehicle group become members of the Vehicle Integration Team. But, the Vehicle Integration
Team has a different set of goals and requirements. And far too often, the gains captured by the Design for Six Sigma teams become dissipated during the integration efforts. Therefore, like the linking that needs to occur purely between manufacturing and engineering, a second link needs to occur between the various phases and groups of the product design cycle. Similar to how product specifications such as peak horsepower follow a product throughout the design process, Design for Six Sigma requirements also need to become integral to the product specifications.

Finally, in order to deal with control, coordination, and creativeness, the automotive industry needs to manage the Design for Six Sigma process effectively. Even though the DFSS process is known for its rigor and standardization, there is a degree to which that is acceptable in a business environment faced with increased competition. Surely, in the area of continuous improvement and re-engineering, standardized processes can provide the necessary edge to gain slight incremental improvements. But, when dealing with newly emerging, disruptive technologies, Design for Six Sigma may actually hinder innovation. Therefore, like any strategy, Design for Six Sigma will provide advantages and disadvantages to a corporation. The successful firms and industries will effectively leverage the attributes of the process while simultaneously using the process to develop a unique competitive advantage.
References


General Motors Corporation and EDS. Robust Engineering Application Training. 1 July 2000.


Henderson, Rebecca. “Going for Growth: Managing Disruptive Innovation (draft).” Chapter 12.


Redinus, Don. “What is Six Sigma?” Breakthrough Management Group


Appendix A: Design for Six Sigma Process (General Motors Corporation)

Figure A-1: Steps 1 & 2

<table>
<thead>
<tr>
<th>Phase</th>
<th>Methodology</th>
<th>Tools</th>
<th>Functional Questions</th>
<th>Tech Review Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CTQ Flowdown</td>
<td>1a. Identify Opportunity/Problem</td>
<td>Warranty Data, JD Power Data</td>
<td>What is your problem/opportunity? What is your quality target? Are your targets consistent with world class?</td>
<td>JD Power Metric, Warranty Cost Metric, IPTV Metric</td>
</tr>
<tr>
<td></td>
<td>1b. Identify Customer Qs</td>
<td></td>
<td>What are your customer Qs?</td>
<td>Team's list of Qs</td>
</tr>
<tr>
<td></td>
<td>1c. Translate Customer Qs to System CTQs</td>
<td></td>
<td>What CTQs have been identified for each Customer Q? Are functional CTQs documented on Performance (or Reliability) Scorecards?</td>
<td>Reliability &amp; performance worksheets (Part no column completed)</td>
</tr>
<tr>
<td></td>
<td>1d. Analyze system CTQs measurement capability</td>
<td>S&amp;A Model Assessment</td>
<td>What is your System CTQs model accuracy</td>
<td>System Reliability and performance % GRR Column</td>
</tr>
<tr>
<td>2. Quality Prediction</td>
<td>2a. Do performance and quality level targets exist for each CTQ</td>
<td></td>
<td>Do performance and quality level targets exist for each CTQ?</td>
<td>System Perf &amp; Rel worksheets Min/Max Columns, Quality target statement</td>
</tr>
<tr>
<td></td>
<td>2b. Generate and justify system Transfer Function/Model</td>
<td></td>
<td>What is your system design? What are its parameters? Alternative concepts? How did you validate system/subsystem model? What is the strategy to get a transfer function if not available?</td>
<td>Structure Diagram, Function Flow Diagram, Explanation/derivation of transfer function, mode, etc...</td>
</tr>
<tr>
<td></td>
<td>2c. Execute Model(s) to determine targets and allowed variation for the model parameters</td>
<td>Analysis.xls</td>
<td>Did you meet your quality goals for all system level CTQs? Are the means and standard deviations for the model parameters achievable? What are the variation drivers: ([(d/dx) \epsilon x] )</td>
<td>Analysis.xls</td>
</tr>
<tr>
<td></td>
<td>2d. Identify the Subsystem CTQs</td>
<td>Analysis.xls</td>
<td>What are the Subsystem CTQs?</td>
<td>Scorecard.xls</td>
</tr>
<tr>
<td></td>
<td>2e. Assess the Subsystem CTQs Capability</td>
<td>Scorecard</td>
<td>Where did you get the data? Are you confident with the data?</td>
<td>Scorecard columns for mean and standard deviation output</td>
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</tbody>
</table>

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### 3. Optimize Design

<table>
<thead>
<tr>
<th>Phase</th>
<th>Methodology</th>
<th>Tools</th>
<th>Functional Questions</th>
<th>Tech Review Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a. Evaluate whether</td>
<td>proposed design meets quality target?</td>
<td>Analysis.xls</td>
<td>What was your mean and standard deviation allocation strategy?</td>
<td>Scorecard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>What in the design would change if cost/quality targets were reduced by 10%? : 50%?</td>
<td></td>
</tr>
<tr>
<td>3b. Communicate critical</td>
<td>parameters to Manufacturing or Suppliers</td>
<td></td>
<td>Are CTQs included on Design documents?</td>
<td>SQR or Engineering Drawing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3c. Develop Manufacturing</td>
<td>and Supplier control plan for CTQs</td>
<td></td>
<td>Are CTQs included in the manufacturing documents?</td>
<td>Process Control Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Product Assembly Document</td>
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### 4. Test & Verify

<table>
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<th>Methodology</th>
<th>Tools</th>
<th>Functional Questions</th>
<th>Tech Review Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a. Confirm that pilot builds meet prediction</td>
<td></td>
<td></td>
<td>Does capability meet allocation?</td>
<td>Scorecard; System Reliability &amp; Performance</td>
</tr>
<tr>
<td>4b. Reline models &amp; scorecards</td>
<td></td>
<td>Scorecard</td>
<td>Have you updated model to reflect capability?</td>
<td>Scorecard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Analysis.xlsx</td>
<td></td>
<td>Analysis.xlsx</td>
</tr>
<tr>
<td>4c. Document the effort and results</td>
<td></td>
<td>Word</td>
<td>Have you issued a report?</td>
<td>Report issued electronic file</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Did you file your scorecards?</td>
<td>Function Diagram - Structure Diagram</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Did you complete the Tech Mem Document?</td>
<td>-Analysis.xlsx - Scorecard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Did you capture the improvements in the ADV process?</td>
<td>Scorecard Mod?????</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Did you capture the changes in the VTS/STS?</td>
<td>Tech Mem. Document complete</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ADV improvements captured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VTS/STS changes captured</td>
</tr>
</tbody>
</table>
Appendix B: Structure Diagram

Figure B-1: Top Level View

PHT Fuel Economy Contributors

Electric Machine (EM) — Engine

Energy Storage System — Transmission

Power Electronics — Controls

— Vehicle

Figure B-2: Detailed View 1

PHT Fuel Economy Contributors

Engine

Electric Machine (EM)

Transmission

Accessory Drive

Rotor

Aux. Oil Pump

Stator

Torque Converter
Appendix C: Function Diagram

Figure C-1: Gain Overview
Figure C-2: Engine Off At Idle Gains
Figure C-3: Decel Fuel Cut-Off Gains

1. Decel Fuel Cut-Off
   - Decel DCO Duration
     - Decel Delay Time
   - Decel Engine Speed
     - Accessory Load
     - Engine Friction
   - Decel Engine Load
   - Frequency
     - Driving Pattern
Figure C-4: Early TCC Lock Up Gains
Figure C-5: Regenerative Braking Gains
Figure C-6: Launch Assistance Gains

LAUNCH ASSISTANCE

- AVERAGE LAUNCH FUEL RATE (w/o assist)
- AVERAGE ELECTRICAL SHAFT POWER
- LAUNCH DURATION
- FREQUENCY
- DRIVING PATTERN

THROTTLE POSITION CONTROL

- AVERAGE LAUNCH SPEED
- AVERAGE LAUNCH ENGINE LOAD

ACCESSORY LOAD

ENGINE FRICTION
Figure C-7: Loss Overview

PARALLEL HYBRID TRUCK FUEL ECONOMY

GAINS

ENGINE OFF AT IDLE

DECEL FUEL CUT-OFF

EARLY TCC LOCK-UP

ELECTRO HYDRAULIC P/S

DOWNSHIFT SYNCRO

PHT UNIQUE 12 V LOADS

COAST BRAKING

42 V BATTERY CHARGING

ELECTRICAL CREEP

MASS PENALTY

LOSSES
Figure C-8: Engine Off At Idle Losses

1. ENGINE OFF AT IDLE
   - ENGINE LOAD
   - ENGINE SPEED
   - ELECTRIC MACHINE EFFICIENCY
   - ELECTRIC MACHINE TORQUE
   - BATTERY STATE OF CHARGE
   - BATTERY AGE
   - DC/DC CONVERTER INTERNAL RESISTANCE
   - AVERAGE CAPACITIVE POWER
   - SES INTERNAL RESISTANCE
   - SES STATE OF CHARGE
   - SES AGE

2. ENGINE RESTART ENERGY
   - RESTART FUEL PENALTY
   - RESTART DURATION
   - FREQUENCY
   - DRIVING PATTERN

3. AVERAGE ELECTRIC MACHINE POWER
   - AVERAGE INVERTER POWER
   - AVERAGE ELECTRICAL LOAD
   - BATTERY INTERNAL RESISTANCE

4. AVERAGE SHAFT POWER REQUIRED
   - ELECTRIC MACHINE EFFICIENCY
   - ELECTRIC MACHINE TORQUE

5. BATTERY STATE OF CHARGE
   - BATTERY AGE

6. AVERAGE CAPACITIVE POWER
   - SES INTERNAL RESISTANCE
   - SES STATE OF CHARGE
   - SES AGE
Figure C-10: Early TCC Lock-Up Losses

- AVERAGE ELECTRIC MACHINE POWER
  - AVERAGE SHAFT POWER REQUIRED
  - ENGINE SPEED
  - ELECTRIC MACHINE EFFICIENCY
  - ELECTRIC MACHINE TORQUE

- AVERAGE INVERTER POWER

- AVERAGE BATTERY POWER

- EARLY TCC LOCK-UP
  - EARLY TCC LOCK-UP SMOOTHING ENERGY

- AVERAGE ELECTRICAL LOAD
  - BATTERY INTERNAL RESISTANCE
  - SES INTERNAL RESISTANCE
  - SES STATE OF CHARGE

- AVERAGE CAPACITIVE POWER

- AVERAGE SMOOTHING POWER

- SMOOTHING DURATION
  - FREQUENCY
  - DRIVING PATTERN

- ENGINE SPEED
  - ACCESSORY LOAD
  - ENGINE FRICTION
  - SES AGE
  - BATTERY STATE OF CHARGE
  - BATTERY AGE
Figure C-11: Electro-Hydraulic Power Steering Losses
Figure C-13: PHT Unique 12V Load Losses

Figure C-14: Coast Braking Losses
Figure C-15: 42 Volt Battery Charging Losses
Figure C-17: Mass Penalty Losses

MASS PENALTY

PHT OPTION CHOICE
Appendix D: DOE 1 Interaction Plots

Figure D-1: Battery/Electric Machine Interaction

Battery/EM Efficiency Interactions

\[
\text{EM Efficiency: } y = 1.1924 + C_2 \\
\text{y = 1.5974x + C_1}
\]
Figure D-2: Electric Machine/DC/DC Converter Interactions

DC/DC Converter/EM Efficiency Interactions

Combined MP

DC/DC Converter Efficiency 80%
y = 0.4045x + C2

DC/DC Converter Efficiency 80%
y = 1.275x + C1
Figure D-3: DC/DC Converter/ Battery Interactions