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Platform Determination Modeling for Existing and New Product Family

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Platform Determination Modeling for Existing and New Product Family

By

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Platform Determination Modeling for Existing and New Product Family

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ABSTRACT

Today's automotive market is a highly competitive industry as many global manufacturing enterprises are competing to increase and dominate market shares. Automotive and other major manufacturers must focus on product differentiation to fulfill customer demands and expectations, increase market share globally and domestically, and reduce design and manufacturing cost.

To meet market demand, enterprises must understand current and future customer expectations as perceptions evolve overtime. Product platform and products family strategies have been implemented widely to offer variations. Assessing and benchmarking platforms and families differentiations - within an enterpriser –are tools used to support and create the most effective balance between market demands and product variations; to avoid self-competition.

It has been noted that there has been insufficient researches to identify the gaps in products differentiations within an enterprise and the market. Differentiations with consideration of the dynamic market, market share analysis, globalization factors, functions, function attributes, and sales prices. The focus of this research is to identify the ultimate number of product platforms and product families of existing and prospective products of an enterprise. The mathematical model discovers the top features and functions needed in the market, and eliminates weak car models which do not meet customer expectations. This identification is achieved through analyzing current products diversification, degree of diversification, product saturation and ability to accommodate more functions.

The developed mathematical model is demonstrated and validated using case studies based on examples from actual situations. It applies to both product platforms and product families. The results showed that the developed model is not limited to the automotive industry only, but it can be applied to other products and industries as well. This work supports the product designer and strategy-makers in the activity decision process to identify needed functions and features to increase market shares and allocate resources efficiently.

DEDICATION

To my parents, Mohamed and Alia; and siblings, Anas, Mokhles and Heba

Beloved Wife, Hasnaa; and two wonderful children, Mohamed and Yasser;

My parents in-law, Abuldsalam and Ibtisam;

My in-laws, Ahmed, Mohamed,

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I WOULD LIKE TO START BY THANKING THE ALMIGHTY ALLAH AND FOREMOST GIVEN ME THE WILL, ENERGY, PATIENT, AND GUIDANCE WITHOUT WHICH I COULD NOT ACCOMPLISH THIS PRESTIGIOUS DEGREE.

I express my sincere appreciation to my supervisor Professor Waguih ElMaraghy for his inspiration, support, guidance, and encouragement in sharing this dissertation. I am grateful for his confidence in me throughout my PhD program.

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My utmost gratitude to my parents for their continuous sacrifice, care, encouragement throughout my life. A very sincere appreciation to my wife and children who gave me all the time and support I needed during my research. A great hugs and love to my both children for their understanding and support. Sons, be proud of your father in the future, and this is the highest degree you can earn academically. I am waiting for the day to see you holding this degree in the medical fields.

Special thanks to all those who taught me the knowledge is the way for honor and helped me to create my mission to continue seeking knowledge throughout my life

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LIST OF ABBREVIATIONS

Adr:	Attribute Distance Ratio
ADSs:	Attribute Deficiency Score
AESs:	Attribute Efficiency Score
ASS:	Attribute Saturation Score
b_1^t:	Function Attribute
Big Three:	Ford, Chrysler, and General Motors
CD:	Compact Disk
CRM:	Customer Relationship Management
D_f:	Dominated product Family
D_p:	Dominated product Platform
DFA:	Design for Assembly
DFM:	Design for Manufacturing
DNA:	Deoxyribonucleic acid
DPD	Delayed Production Differentiation
DSM:	Design Structure Matrix
DSP:	Decision Support Problem
$\mathcal{E}$:	Enterprise
EP_p:	Platform Efficiency Power
F:	Product Family
$\mathcal{F}$:	all functions offered by all products in the study case
F_i:	Any Selected Product family
F_N:	Number of Product Families
f_t:	Any random selected function
FE_p:	Family Efficiency Power
FBS:	Function Behavior State
FDI:	Family Diversification Index
FDFAe:	Exclusive Family Differentiation Functions Analysis
FDFAs:	Standard Family Differentiation Functions Analysis

FDSs: Family Deficiency Scores for standard functions

FESs: Family Efficiency Score for standard functions

FSI: Family Saturation Index

FUI: Family Unsaturation Index

FUSe: Exclusive Functions Unsaturation Score

FUSs: Standard Functions Unsaturation Score

GM: General Motors

M_n: Number of product model in every platform

$m_{i,r}^t$: Assigned to each function available in a product

M_s: Market Share

MPG: Mile per Gallon

NA: North America

OEM: Original equipment manufacture

P: Product platform

PC: Product Configuration

PDFAs: Standard Platform Differentiation Function Analysis

PDFAe: Exclusive Platform Differentiation Functions Analysis

P_N: Number of Product Platforms

PDI: Platform Diversification Index

PDM: Product Data Management

PPDEM: Product Platform Concept Exploration Method

QFD: Quality Function Deployment

RPPD: Reactive Product Platform Design

SMPDM: Module-based Platform Design Method

T_t: Number of attributes in each function

U_l^t: Function Attribute Value

VE: Value Engineering

1. CHAPTER ONE - INTRODUCTION

This chapter gives a brief review and historical introduction to the automotive industry, the motivation behind the presented research, the objective and problem statement, the expected benefits and research outcomes, and the market analysis of the automotive industry. A historical trend and ramp-up introduction of product platform and product families to the market will be presented, and how the North American (NA) market domination by the big three (Ford, Chrysler, and General Motors) changed overtime with increase invasion of transplant manufacturers to North America. Product quality and product family variation becomes major key players in the market. Majority of transplants manufacturers entered the North American market with limited number of product platforms. Shortly after, new vehicle platforms, which represent vehicle size in the industry, started to appear to accommodate end-user expectations and culture. BMW entered the North American market with small to large vehicle sizes. But recently, new Sport Utility Vehicles (SUV) were designed and presented to serve certain market segment. Honda never had car-van platform in its fleet. The market demanded new vehicle size to serve long haul family trips as part of the American culture. The Odyssey van was introduced as a result to increase market share. The industry is full of examples and will be presented graphically.

1.1 Background

The automotive history started back in the mid-eighteen century when steam engines were engineered to transport rich and wealthy people. In 1806, the first automobile powered by an internal combustion engine running on fuel gas appeared in the market (Eckermann, 2001). The year of 1885 witnessed the introduction of the combustion engines running on modern gasoline. Cars powered by electric energy briefly appeared by the end of the twentieth century, and widely introduced to the mass production in the early twenty-first century.

The production of automobiles was first introduced by Karl Benz early 19th century in Germany, and by Emile Roger in France. The first formed company exclusively to build cars was established by Panhard Levasor in France, which introduced the first four cylinder engine. Two years later, Peugeot started to build cars. By early 1900s, the automotive industry started to expand and take off in Western Europe. By 1903, France built 30,204 vehicles which represent 48.8% of the market share in the automotive world (Crucean, 2010).

A business pioneer named by Ransom Eli Olds and his Olds Motor Vehicle Company, later known as Oldsmobile, dominated the production industry of automotive. The production line of Oldsmobile started in1902, as the Thomas Jeffery Company developed the second mass production line to produce and sell 1,500 Rambler vehicles within the first year. In one year, Henry Ford Company introduced the Cadillac and Ford brand and started producing vehicles in the thousands.

The innovation of automotive vehicles was not limited to the vehicles themselves. The petroleum industry to propelled vehicles started to pick-up and produce gasoline engines (Sherman, 1988). The first patent in the automotive industry was granted to George Selden in 1895 for a two-stroke automobile engine (U.S. Patent 549,160). The patent was licensed to most and major NA manufacturers.

Today, the automotive industry, globally and specifically in North America, is an extremely competitive market due to the numerous transplant enterprises that are aggressively competing for market share. The NA market back in the 1960s was strictly dominated by what is called the American Big Three (General Motors, Ford Motor Company, and Chrysler), Capturing more than 95 percent of the total NA market. Six different automobile models, essentially different platforms, were adequately sufficient to capture 80% of the sold vehicles in 1955 (Womack *et al.* 1991) and maintain domination in the market shares. According to Automotive Industries Magazine (2012), currently, General Motors, Ford, and Chrysler, rank second, fifth, and thirteen, respectively. Toyota ranks number one in the world motor vehicle production with 8.55 million vehicles.

In the early 2000s, the Vice President of Daimler Chrysler clearly stated “Twenty years ago, we did not have as much competition, the market was not as fragmented, and you could enjoy high volume. We can no longer expect to enjoy these huge half million per platform sales volume anymore (Carney, 2004). As Henry Ford stated in regards to the conventional dedicated mass production strategy “any color you want - as long as it is black (Ford, 1922).” This mentality-set in business must be changed to meet market demand and customer expectations.

Manufacturers need to improve efficiency and be more responsive to market demand with more variations with least development cost. Product platform strategy was introduced by sharing components and modules across the product family; if possible, to accommodate size and production capacity. Modular commonality enabled automotive manufacturers to offer more product families as well. The most important concept of product families is to distinguish between standard and exclusive features, and offer new functions which are not available to the market. For example, Toyota introduced Lexus as the second product family to the NA market early 1990s which offers new features which and functions which are not available in the Toyota family. Another example, BMW introduced the new Mini family which offers unique functions and features not offered by the BMW family. Figure 1.1 illustrates the relationship between product platforms and product families. Essentially, a product family consists of several platforms which offer different functions for different market segments to meet end users’ demands.

In contrast, enforcing product platform strategy by sharing too many components on different vehicles has several potential drawbacks, tradeoffs with performance, different effects depending on stakeholders, loss in brand identity due to excess use of common modules, and insufficient differentiation between each other. Nevertheless, disadvantages apply on product platform as well. Due to high cost of introducing new platform, enterprises were very reluctant in investing new products without depending on existing platforms, at least partially. What is needed is an effective methodology and strategy to evaluate current platforms and families offered by the manufacturers. The strategy is intended to, either introduce new platform/family, or eliminate an existing platform/family to maintain brand identify, reduce validation and manufacturing cost, and increase market shares in the competitive global market; of course with respect to available technology and finish-good prices.

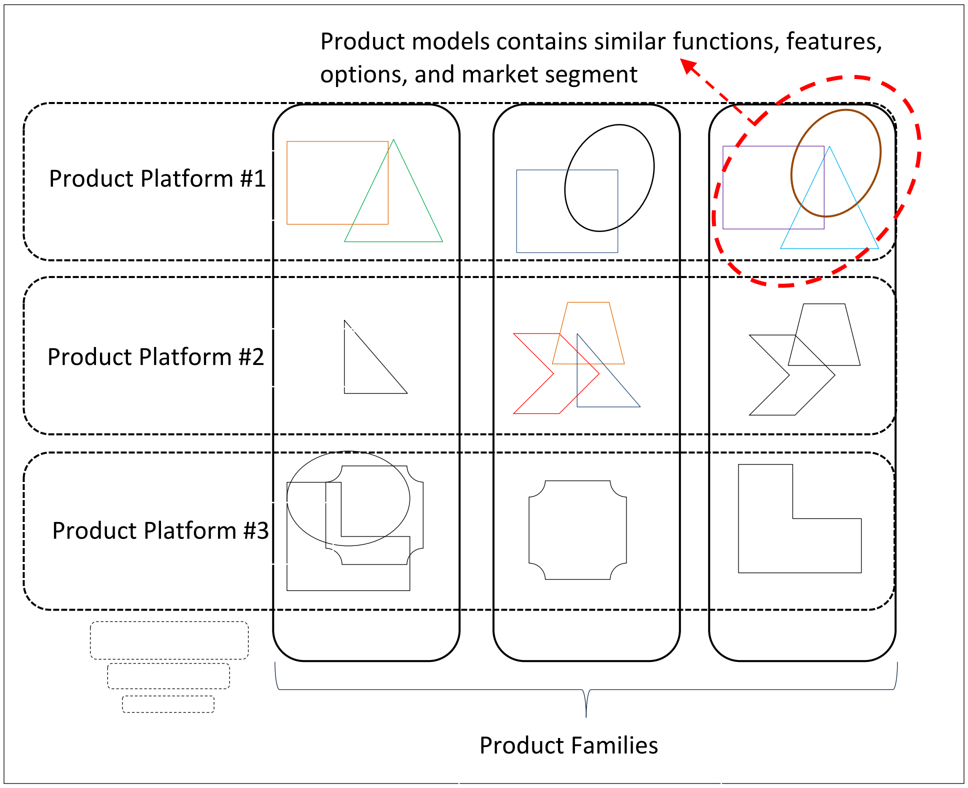

Figure 1.1: Enterprise Products Structure

1.1 Motivation

Figure 1.2 illustrates in details the NA market share between the NA manufacturers verses the international manufacturer from 1986-2011. The trend shows, for North America Market, how the market share for the NA manufacturers declined from 70% in the early eighties to 40% in 2011. Nevertheless, the international competitors inclined from 27% to 60%. If the trend continues for another ten years, the market share would shift to 75% for international manufacturers, and 25% for domestic manufacturers. The future strategy seems clear. Domestic manufacturers are clearly not vigilant enough regarding this potential threat. The span in product variations in platforms and families is one of the most important factor to maximize market- share and probability, but this maximization must be expanded systematically in an optimized manner.

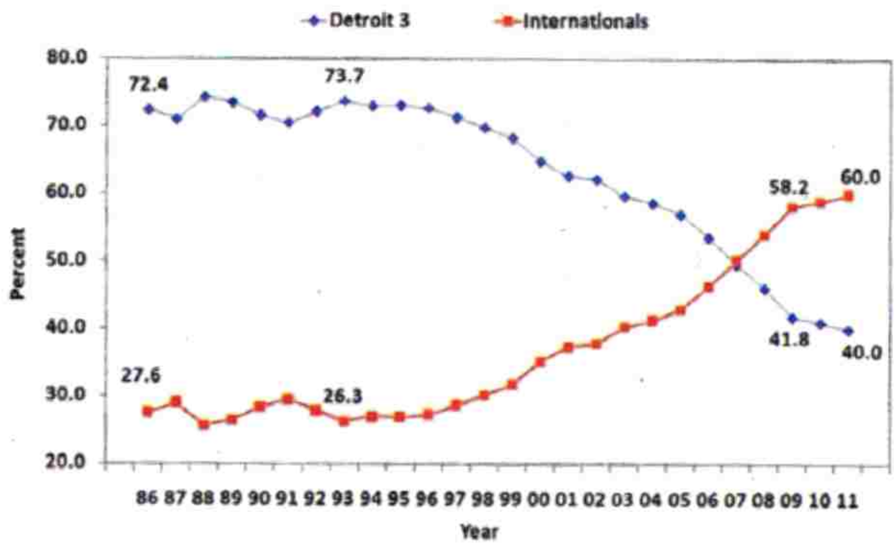

Figure 1.2: US Manufacturers Market Shares Versus International Market Share (Automotive Industries, 2012)

The global market forced enterprises to offer unique products to differentiate them among other competitors. As a matter of fact, the automotive market is targeted by numerous numbers of manufacturers to serve different market segments. The competition becomes more and more difficult and costly. Successful differentiation attracts more end-users, benefit brand image, generate more revenue, and increase market shares. Platform-based product development which is based on sharing modules and components leads to cost reduction in development, rapid response to market demand, reduce design cycle time, and manage product standardization. In contrast, similar products have a significant negative impact on market shares as the products do not offer unique functions and function attributes. In addition, unsystematic product variations essentially lead to "*self-competition*".

By analyzing the historical trend of the NA marker shares by each automotive manufacturer, as shown in figure 1.3, we clearly observe that NA Original Equipment Manufacturer (OEM) started to decline as soon as the foreign automotive manufactures entered the North American market. Various factors are involved in the downtrend and lose of market shares. The transplant brands started to gain market share NA slowly but surely. Toyota witnessed a positive milestone when Lexus was introduced to capture the new market segment, luxury vehicles.

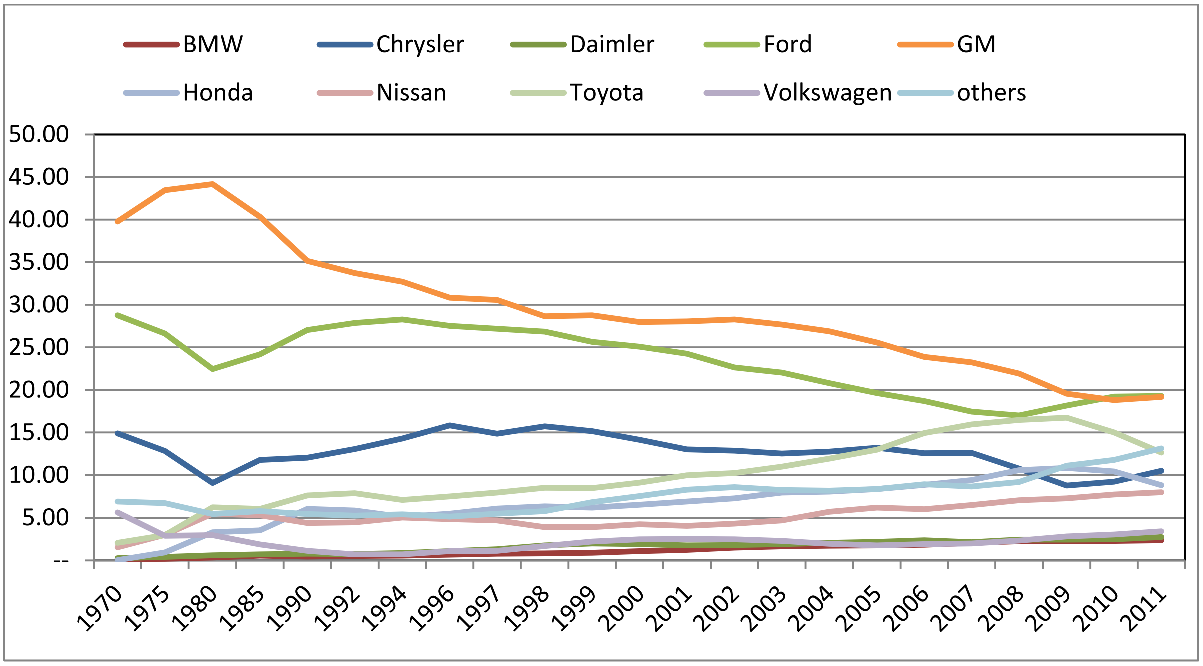

Figure 1.3: North America Market Share per OEM

By conducting a further analysis on one of the NA manufacturer, such as Ford Motor Company, as shown in figure 1.4, Ford started to lose market shares in the early 1990s with the entrance of foreign manufactures to the NA market. Ford struggled to maintain position and decided to build more platforms to offer wider product variations. The trend kept declining Ford introduced more product families to survive. In the late 2000s, Ford realized that with limited product families and more platforms, manufacturing will boost its position in the market. This is clearly observed in the chart in the year 2007, as Ford made a crucial strategy change in its product families and decided to sell Jaguar, Volvo, and give away Mazda shares, including the Mercury family. The reduction in product families and maintain product platforms bounced the market shares up. Other strategy included product standardization across the globe. Fiesta, the top seller model in Europe was introduced to the NA market as part of "One Ford" strategy in the global market.

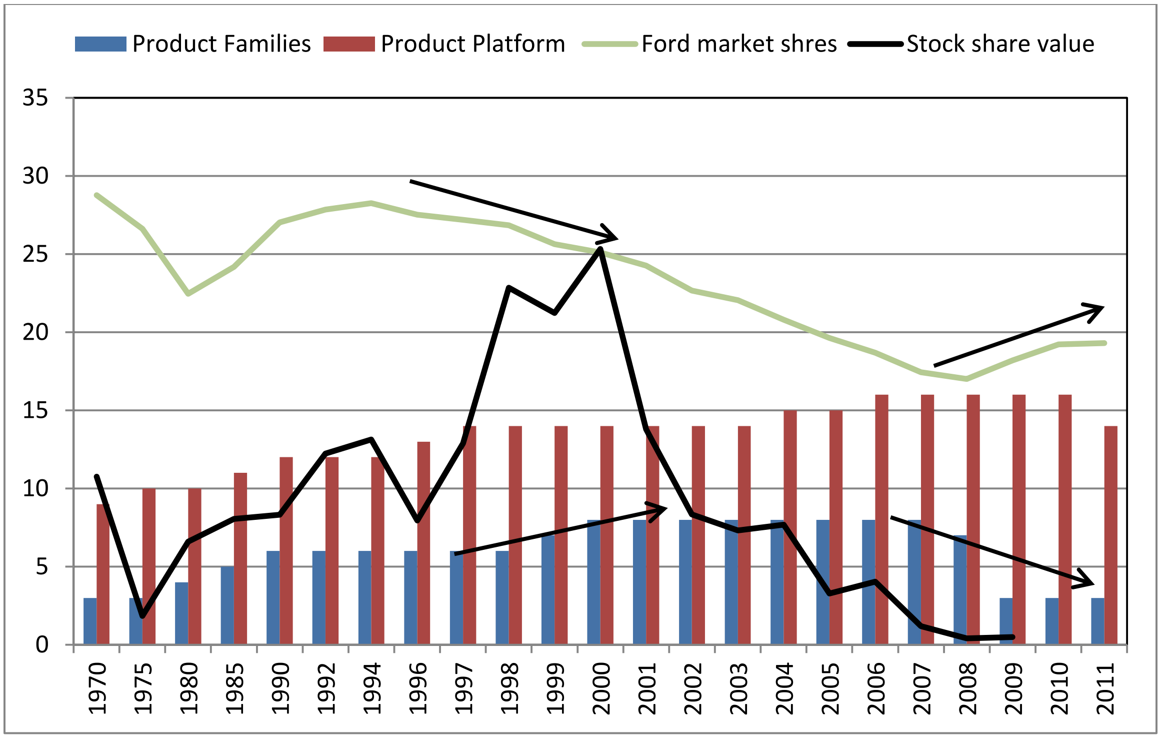

Figure 1.4: Ford Market Share History

Another real and live example to review and analyze from the industry is General Motors. General Motors has a very long history for being a giant key player in the automotive industry, at least from number of employees and the number of vehicles sold globally prospectively. The trend in figure 1.5 illustrates GM's market shares in NA. We strongly believe that despite the increase of product platforms between years 1992-2002, GM kept loosing shared due to self-competition factor within the enterprise. A new platform, for example, van-vehicle should increase the market share as common sense. However, the van was offered across three product families: Pontiac, Chevrolet, and Oldsmobile. In other words, the cost of design, resources, validation, supply chain management, and manufacturing were three times more than what it was supposed to be. In the year 2008, GM realized that a few product families need to be discontinued from the market to reduce cost. As a result, Hummer, Oldsmobile, Opel, Hummer, and Pontiac shut down their manufacturing doors. The budget of these product families was dedicated to improve the remaining products with new technology and new features.

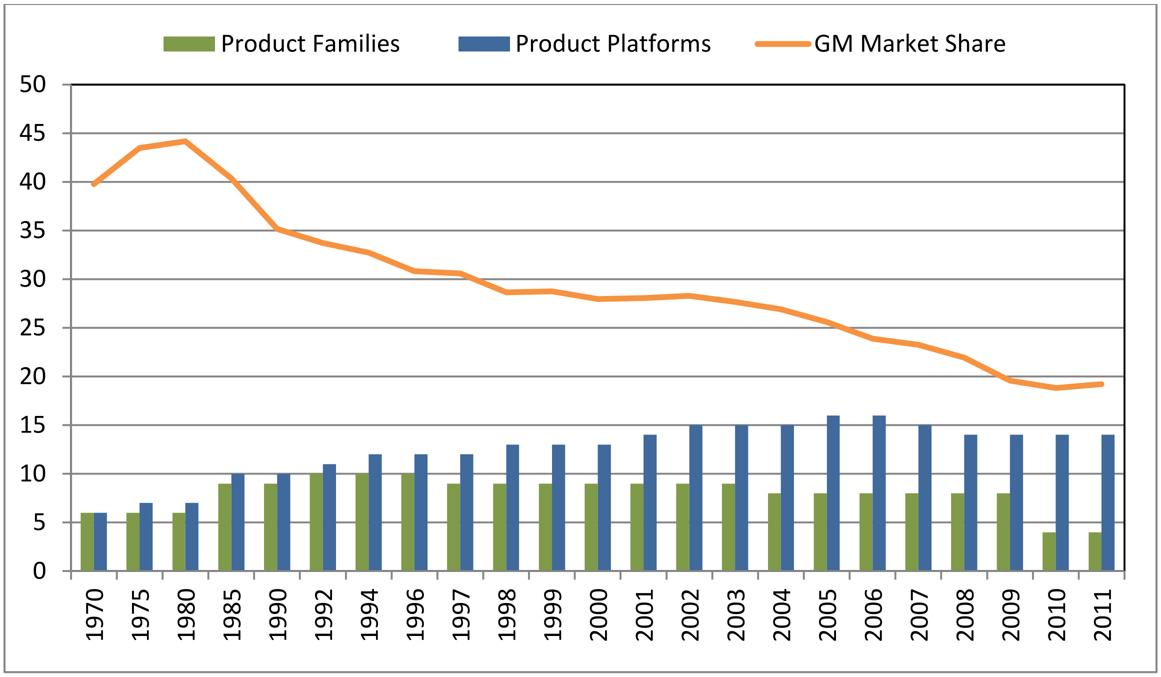

Figure 1.5: GM Market Share History

There are several factors to differentiate products among competitors to maintain and increase customer perception, as illustrated in in Figure 1.6: strong brand, function and function attributes, strong resale value, cost, design and appearance, market segments, performance, quality, and technology. Customer perception toward design appearance, quality, and technology are beyond the scope of the research.

The motivation of this dissertation is to offer a mathematical model approach to the automobile manufacturers to better understand the creation of new product platform and product family. The approach will enhance the introduction of new vehicle model which offer customer needs and expectations. Nevertheless, better understanding of market needs leads to reduction in design cycle time, repaid response to the market, increase market shares, and profitable and healthier financial balance sheet. Overall, the phenomenon of self-competition will be illustrated as to be avoided and implemented as part of the long-term corporate strategy.

Product diversification analysis enables enterprises to appropriately design and offer unique products to the market. The analysis will pin-point the missing functions within the families, across the platforms, compare to the market, and develop what is

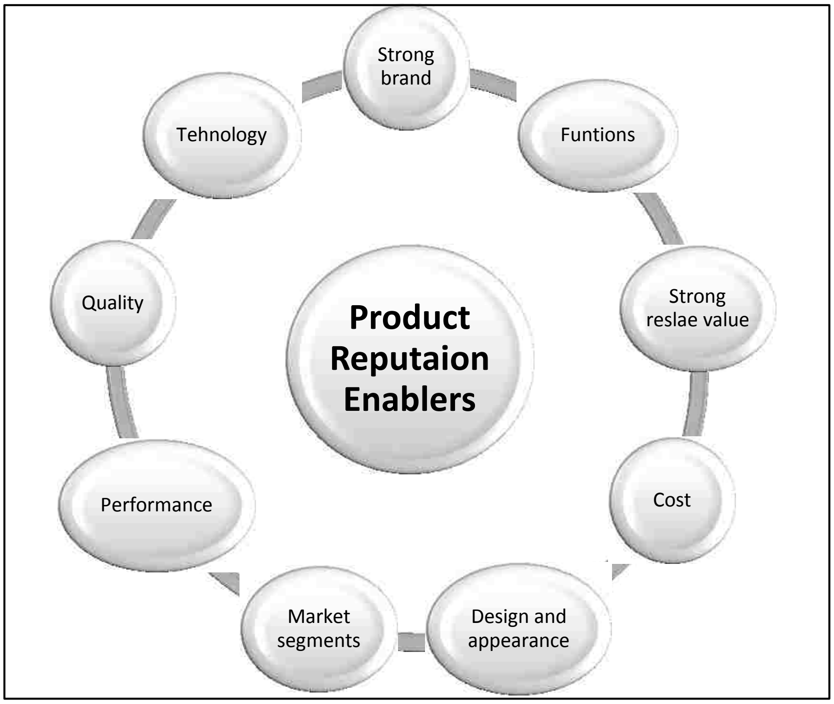

Figure 1.6: Product Reputation Enablers

required. For this reason there is a need for methodology that evaluates current efficiency of product differentiation and the relationship between market demand and existing products.

Overall, the number of product families per enterprise is decreasing overtime, and product platforms are increasing over time. The reason is because consumers are after vehicle size and quality to fulfill specific needs for a specific segment. The cost to develop a product platform does not come cheap. Enterprises should focus on developing platforms within the core family rather than bandwidth of families. Therefore, a formulated mathematical model is needed to identify the profitable family and platform through:

- Efficiently allocate budget and development cost resources
- Efficiently allocated engineers, designer, and manufacturing plants recourse
- Reduce development and certification cost on one platform in one family rather than two families
- Assigned surplus budge on developing and improving performance
- Assigned surplus budget to offer more features and functions
- Prove that expanding product families not necessarily increase market shares

1.2 Dissertation Statement

Increasing market shares is extremely important to maintain a healthy and a profitable organization. Product variation is essential to meet objectives and corporate strategy. However, unsystematic approach to product variations is risky, and the trade-offs between excessive products variations which potentially leads to self-competitions must be every company concerns. Self-competition generates unnecessary validation costs, consumes resources efficiencies, and reflects negative perception on brand loyalty and image. The problem of the automotive industry, especially the NA manufacturers, offers various and wide range of automobile varieties without studying the market adequately. Product families may create self-competition and jeopardize market share. Variations should be initiated and created by increasing more product platforms to serve and target new market segments. This dissertation identifies the relationship and correlation between product functions and function attributes to the market shares and enterprise product families and platforms. This relationship enables enterprises to determine the appropriate number of product platforms and families which offer as much functions as possible to the market with least development and manufacturing cost. Redundancy and self-competition should be avoided to achieve a healthy and profitable balance sheet. The dissertation statement can be defined as"

"Increasing the Product Family within the North American automotive industrial enterprises context; Increasing Product Family may create self-competition and jeopardize market share. Whereas Product Platform would increase market share by targeting more market segments"

1.3 Research Scope

The scope of the research is to propose a mathematical model for an enterprise portfolio to reduce development cost, and potentially increase market share by identifying the appropriated product platform for the North American market. The model evaluates and analyzes the functions and function attributes in relationship to the market share. The mathematical model is not based on a longitudinal study to identify the relationship between enterprise portfolio and market share, a random production volume is selected randomly to tow different case studies to validate the model.

The research has some limitations which are considered beyond the research scope, and to be considered for future studies and researches. We believe that product family and product platform have significant contribution to the market share, but they are not the sole causation. Customer loyalty and reception toward a brand is not considered in this search. The relationship between market share and market uncertainty considered as input variable in the mathematical model.

1.4 Research Objective

The main objective of this research is to formulate and develop a mathematical model to quantify and evaluate the current enterprise products and vehicle models on both levels: product platforms and product families. The approach will present a relationship between product family, product platform, market share percentage, and available features, functions, and function attributes. Furthermore, the approach will provide a comprehensive evaluation of product models within the same platform and family, and then determine the appropriate number of vehicle models. The second step is formulating a mathematical model to evaluate the number of current product platforms offered by the enterprise within the same family, and understand if platforms cover all market segments. Then, evaluate the enterprise product families' diversifications, and identify the most diversified family. Most diversified family does not necessarily mean it contains all features and functions. Further analysis identifies the saturation level of product families to identify missing functions. The third level of the evaluation is to benchmark over all product families with the market. This evaluation identifies the efficiency and deficiency of available product families, product platforms, and product models. Finally proposes solutions to increase market shares for future business growth. Figure 1.7 demonstrates the dissertation objectives in a systematic approach.

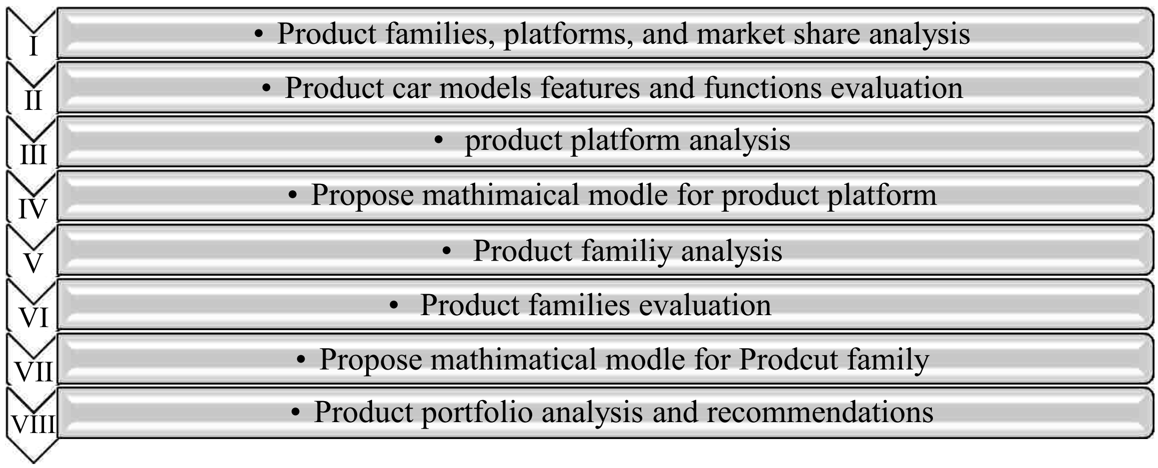

Figure 1.7: Research Platforms and Families Modeling Process

1.5 Research Contribution

The major contribution of the dissertation is the introduction of product platform and product family design process, taking into account annual production volume, market share, functions, and function attributes. The mathematical approach presented a relationship between product family, product platform, market share percentage with respect to offered features, functions, and function attributes. In addition, the proposed approach provided a comprehensive evaluation of product models within the same platform and family, and then recommended the appropriate number of vehicle models, families, and platforms. Further analysis identified the saturation level of product families to identify missing functions. Finally, the proposed mathematical model evaluated and identified the efficiency and deficiency of available product families, product platforms, and product models.

1.6 Dissertation Limitation

This dissertation focuses on the evaluating product platform and product families in relationship with functions, function attributes, and market. Its contribution is to establish a systematic process to create a product family that consists of platforms to serve all market segments. Products functions and attributes are evaluated from functional and value perspective. Platform development and process flow is beyond the scope of the research. Manufacturing flexibility and assembly capacity are not considered in the proposed mathematical model. Other factors not considered in the research are:

- Market uncertainty in customer demand due to marketing campaigns, discounts, interest rates, and old model discount deals
- Customer perception and behavioral change based on previous experience
- Market demand and supply outside of NA
- Global and domestic market inflation and financial fluctuation
- Global and individual Culture impact toward product, enterprise, or reputation
- Product design in terms of shape, appearance, and color variations
- Implications of supply change management

1.7 Chapter Conclusion

The automotive manufacturing industry has changed dramatically in the last twenty years and the world has become more global. Market domination is not a valid business model anymore as competition increased over time. Customers have become more knowledgably about manufacturing, quality, reputation, technology, prices, and features offered by each and every OEM. Transplant manufacturers comprehended the NA market expectations, when they entered the globalization era. Where the old big three manufacturers suffered from three things:

1) Maintain business model-set with the impression that customers will remain loyal regardless of technologies offered by competitors

2) Lack of market analysis to predict customer needs. Product variations should be systematically and thoroughly studied. Too many variations do not guarantee profit.

3) The big three should know the North American culture more than anyone else, but the lack of responsiveness to market needs ranked them behind.

According to the market trend shown in figure 1.3, customers tend to lean toward better quality and more reputed manufacturers with lower depreciations. Even the demand on vehicle segments has changed overtime, as shown in figures 1.8. Customers started to show interest in foreign brands, requesting different vehicle size, as they move away from domestic brands. Manufacturers started to realize the needs for different vehicle sizes and platforms, and they were very responsive.

Therefore, increasing market shares and prompt response to market demand is a must for any manufacturer to maintain a profitable financial sheet. A response to customer needs with the appropriate product variation in a systematic approach is extremely important. Identifying product variations, product platform, and product family wisely reduce the risk of self-competition and redundancy in product functions. An enterprise with different product families should work hand-in-hand as one entity and disregard internal competition between different divisions and departments.

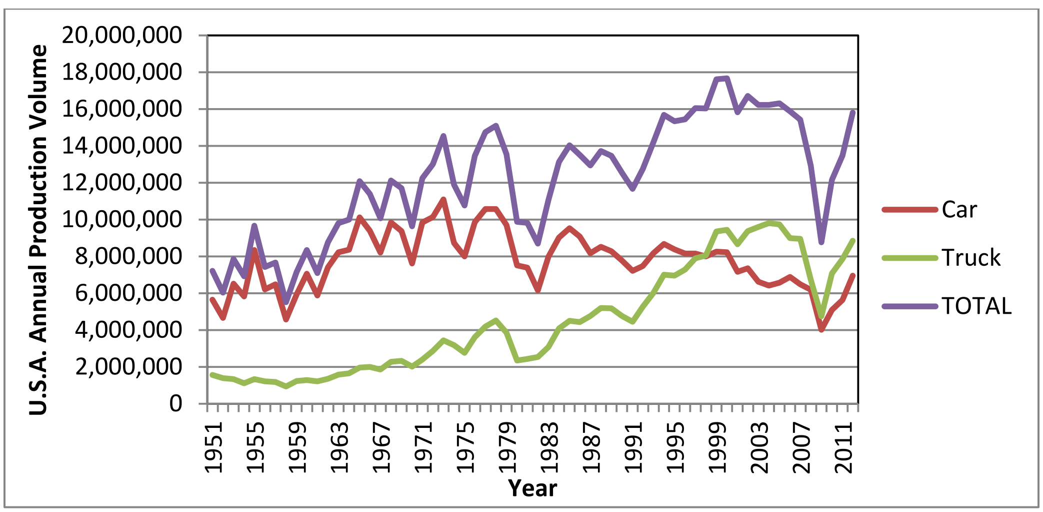

Figure 1.8: NA Annual Vehicle Production Volume – Cars Verses Trucks

Therefore, this research will propose and develop a mathematical approach to evaluate current and future design of product models, product families, and product platforms. The approach will propose a solution to increase market share and profitable revenue.

2. CHAPTER TWO - LITERATURE REVIEW

This chapter presents a deep literature review related to the research. The chapter will present previous and current researches conducted by various scholars. Researches were conducted in fields, industry and academia. The literature reviews will highlight gaps and propose solutions.

2.1 Introduction to Product Design and Development

Product design, or otherwise known as industrial design, creates the first broadly functional description of a product together with its essential visual conception. Product development is known a set of tools and processes dedicated to design new products from inceptions to the point of manufacturing or production. It is described as a modified product based on sets of feedback of information from various downstream of product

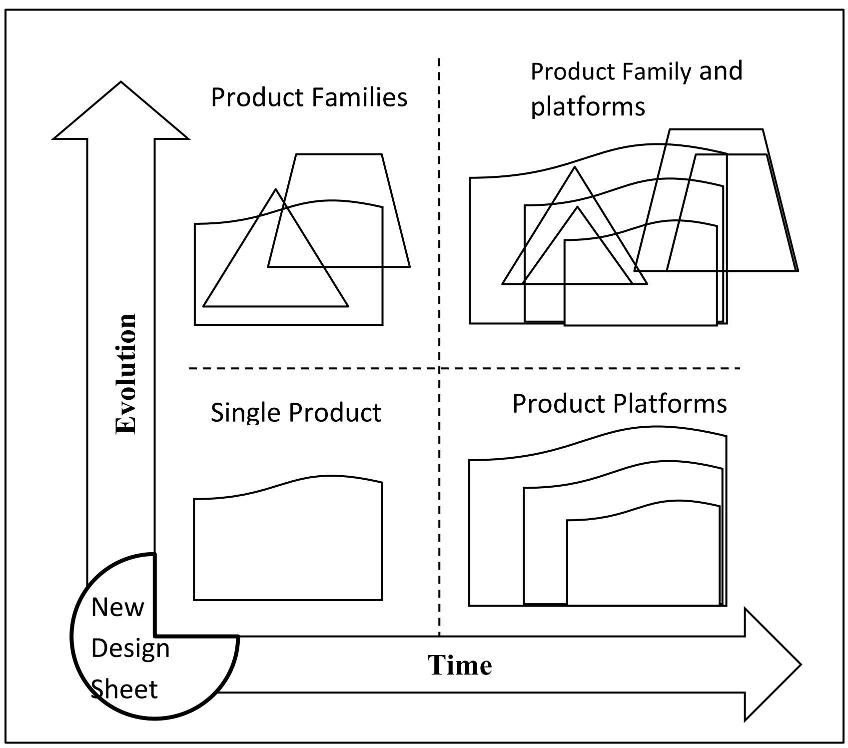

Figure 2.1: Product Development Cycle Overtime

realization activities to be use in designing, evaluation, redesigning parts, and assemblies

(Dixon, et al. 1995). Products are modified over time to present new generations of new products, design models, or technologies. Generally, new products do not start from clean design sheet; they are driven from existing products in response to market demand and competition. Figure 2.1 illustrates the product design evolution and development overtime.

An enterprise starts building with a reputation and presenting its entity to the market by introducing a new car model in a certain product platform. Over time, a new platform could be introduced by utilizing some modules and components from current the production. Over time, the enterprise builds a product family with various numbers of platforms. The first product family may not offer all expectations to the end-users. New platform could be introduced as well. For example, Tesla Automotive is a new vehicle manufacturer in the automotive industry. The first car model was introduced to the market was a high-performance hybrid mid-size vehicle; couple of years later, a new mid-size Sport Utility Vehicle (SUV) platform was offered to the market to serve new a market segment. Two different platforms are available and more to be generated in the near future. Different product platform usually offer different features, functions, and options, and essential target different market segments in different geographical areas.

The pressure to adopt new methods to improve product introduction has been recently intensified. Varieties of various development methods have been implemented by many companies using different tools and techniques in a response to cost, quality, product customization, produce life-cycle, environmental regulation, government regulation, and innovation. In the last couple of years, companies focused their attention on modularization, standardization, platforms, and product families to improve New Product Introduction (NPI) to the market. Companies realized the importance of shortening the product design cycle to be responsive as fast as possible to the market demand.

It has been estimated that as much as fifteen to seventy percent of engineering effort is currently devoted to track design progress during the product realization process (Erdeen et al, 1990; Puttre, 1991; McIntosh, 1992). Product realization is a set of cognitive and physical processes by which new and modified product are conceived, designed, produced, serviced, and disposed. In other words, product realization portrays a cradle-to-grave product design cycle.

Platform design is a popular method of increasing product variation and reducing costs due to the use of common components. Meyer and Lenhnerd (2000) define platform as a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched.

The design process for derivative product development and platform are similar. However, the inputs and outputs are different. Platform process could start from new or existing design, where the outcome of the platform process is the beginning step for the derivative products, which mean product variations with different options. For example, Dodge Ram 1500 is pick-up platform; the truck comes in four different variations, regular cab with 6.4 feet flatbed, regular cab with 8.8 feet flatbed, double cab with 6.4 feet flatbed, and an extended double cabin with 5.6 feet flatbed (Figures 2.3).

Platform project produce platforms only and derivative project-product families-outcomes are products to be introduced to the market in readiness for launching.

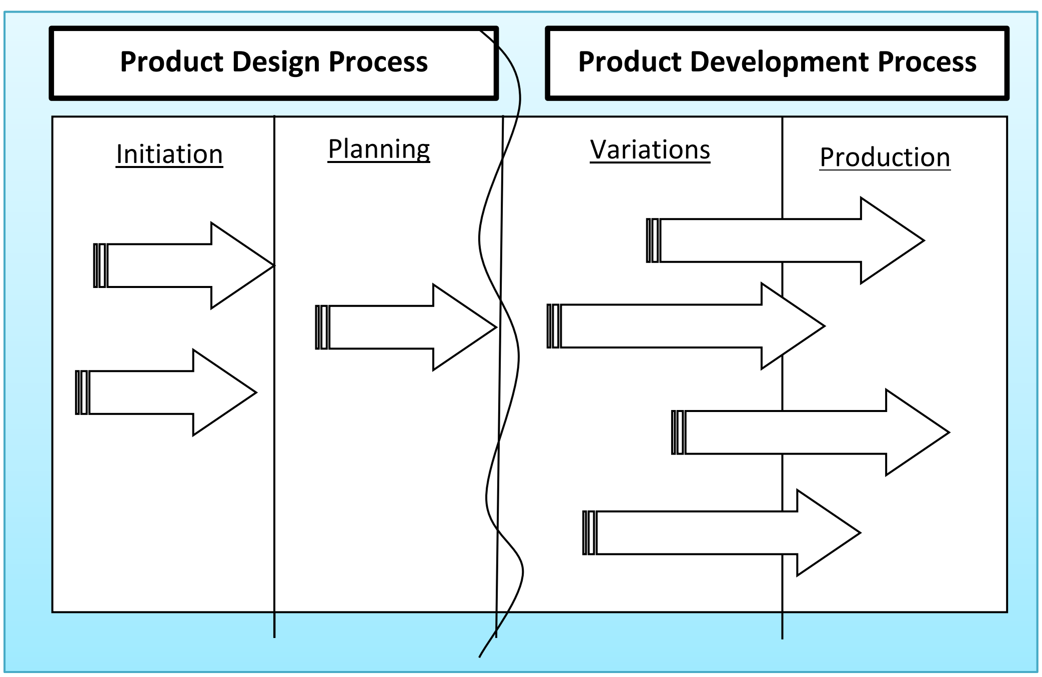

Figure 2.2: Traditional Product Platform Design and Product Development Process

Figure 2.2 illustrates the concept of two platforms that can derive five variations and the relationship between them in the product design process.

According to Ulrich (1995), product architecture is a scheme where the physical components are associated with functional elements to form a different product. The two mentioned dimensions are classified as physical, which refers to the group of physical components and assemblies to enable function, and functional elements which are the group of operations and transformations that contribute to the general functionality of the product. In addition, the product architecture is established after defining the market target, the product technology tendencies, and the identification of all the general family product specifications (Ulrich *et al*., 2000).

To translate the above figure (2.2) from theory and idea to a practical example in the automotive industry, Figure 2.3 illustrates the platform design and variations taken into production. More vehicle variations is illustrated in Appendix A

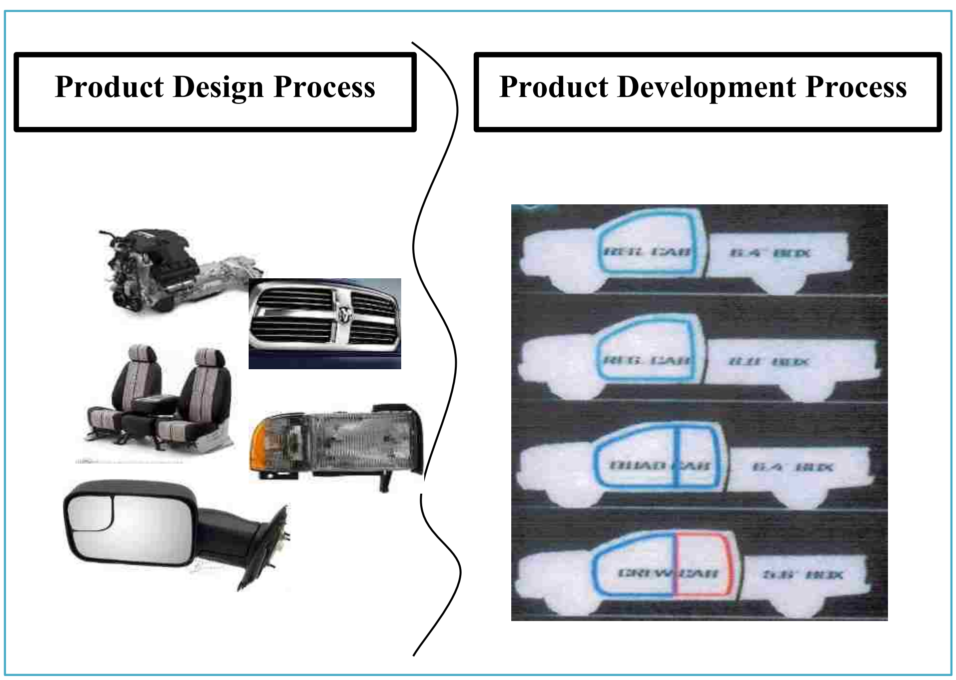

Figure 2.3: Product Design Process and Variation

2.2 Product Architecture

Product architecture is an arrangement of functional elements in the building blocks of the system and it could be developed by defining a mapping of functional and physical elements considering interface specifications between components or modules (Mikkola, 2000). The application of product architecture results in modular product design to accommodate agile product development (Anderson, 1997). Other researchers, including Ulrich (1995) defines architecture in general as the scheme by which the functions of a product are allocated to physical components, where Crawley *et al*. (2004) define system architecture by replacing physical components with entities that could be functioning, whether components are physical or non-physical. According to Crawley (2004) system architecture is an abstract description of the entities of a system and the relationships between those entities.

In general, all researchers agree on one common definition: which is the arrangement of elements of the product. In all cases, product architecture deals with either the physical structure of the product, the function of the product, or with the mapping between the two elements. This dissertation will be adopting Crawley's definition with respect to Ulrich's definition which will be explained later on to generate new products. Several works consider the product architecture as the baseline for product family development, (Jiao and Teseng, 1999; Dahmus *et al*., 2001, Mikkola and Gassmann, 2001)

2.2.1 Product Architectural Models

Researchers created and established several ways to represent product or system architecture. As mentioned previously, Ulrich (1995) defines the product architecture as the scheme by which the functions of a product are allocated to physical components. On a system approach level, architectural was defined by Maier (2000) as a structure of a product, process, or element. System architecture is an abstract description for the entities of a system and the relationship between those entities (Crawley *et al*., 2004). The following sections will briefly present few common architectures that strictly concentrate on physical elements such as components, sub-system, or functional elements that include product functions decomposition.

2.2.1.1 Function Structure Model

Several modular product design methods are derived from function diagrams in which the flow consists of energy, material, and signal or information that enter and exit the sub-function system (Pahl *et al*., 1999). A new design structure matrix was developed by Pimmler and Eppinger in 1994 to include four types of interactions: spatial, energy, information, and material (Pimmler, 1994). Adding addition factor to the system function indicates the possibility to either add or remove more factors, or ending up with unbalanced number of elements between the input and the output. The objective of this model is to satisfy and improve design method through product recyclability with respect to physical structure and material compatibility (Coulter *et al.* 1998).

Figure 2.4 presents a single function structure block model to demonstrate the flow information, energy, and material between and through functional blocks. This process makes this model appropriate utilization for the electromechanical products.

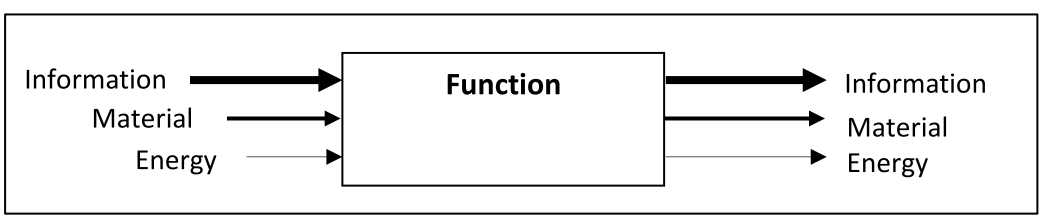

Figure 2.4: Single Function Block of a Function Structure Model (Pahl et al., 1999)

2.2.1.2 Design Structure Matrix

Organizing product development tasks to minimize unnecessary rework, help managing, and speed up the development process can be achieved by utilizing the Design Structure Matrix (DSM), which is one of the most popular design method. Most organizations adopted the DSM model initially to organize massive communication activities within the organization between individuals and departments. Some companies expanded the benefits toward the product design process to standardize procedures and functions. In addition, DMS can be used to define modules within a single product's architecture. Functions or components are mapped rows and columns to represent their interactions and correlation to each other. Figure 2.5 presented by Pimmler and Eppinger (2001), and Blackenfelt (2004), illustrates the interactions and relationships between functions. Functions in both rows and column could represent components, parts, or modules. Functions from rows with an affect or connection with functions from columns, number "1" will be assigned in the crossed box. The presence of digit "0" indicates no relationships between crossed functions. Furthermore, interactions can be ranked from -3 to 3 based on the relationship strength. Single function block model can be implemented in every crossed box to include Spatial, Material, Information, and Energy. The Relationship between functions can be broken down into four categories: Energy, Information, Material, and Spatial. A clustering algorithm is applied to maximize interactions between functions, and each formed cluster is considered as a module.

Researchers established this type to product architecture to concentrate on the interfaces of the modules to simplify the design process and the apparent complexity of the product architecture. However, the model leaves more business oriented factors and product functionality up to the designer's judgment after first simplifying the architecture.

	Function 1	Function 2	Function 3
Function 1	1	2	
Function 2	1		S I E M
Function 3		-3	-1

Figure 2.5: Design Structure Matrix (Dori, 1998)

2.3 Modularity

The general definition of modularity is the relationship between functional products and physical structures such as:

1- There is one-to-one or many-to-one correspondence between the functional and physical structures; or
2- Unintended interactions between modules and minimized (Ulrich and Tung, 1991; Ulrich, 1995; Erens and Verhulst, 1997).

Modularity is commonly known as using structurally independent modules to form product architecture. Where, modules represent functionally independent units that consist of more than one part of components and are meant to fulfill one or more technical functions, ElMaraghy (2009), which are considered the main enablers and prerequisite for a product to offer platform variations. Some researchers such as Ericsson (1999) and Baldwin (2000) define modularity as structurally independent building block of a large system with well-defined interface. Modules can be simply replaced, exchanged, or combined with each other at the differentiation line stage to achieve product variant (Jose and Tollenaere, 2005). Hubka and Eder (1998) defined modular design as constructional element into suitable groups from which many variants of technical systems can be assembled. Elsewhere, modularity has been divided into three categories: design modularity, manufacturing modularity, and customer modularity

(Mattson, 2001). Beside the similarity between the physical and functional architecture of a product, a module is an integral physical product substructure that establishes some type of correspondence with a subset of a product's functional model, and has a minimal interaction with other modules or the rest of the system.

Modularity can be classified into two types:

1- Hard module, which is a set of physical components couple together to form an independent function
2- Soft module, which is a set of various codes and commands compiled together in software to execute a single of multi tasks. Software modules can be updates, modified, and replaced as needed.

Product platform variation and diversification is initiated by utilizing the modular concept appropriately as long as designers minimize the physical interactions between components (Ulrich and Tung, 1991), and standardize the interaction between physical and functional design architecture within the product family which provide flexibility in product design architecture (Ulrich and Eppinger, 2012). Most expert designers cannot pin-point what products are more modular when product architectures become more complex. Improving a product's modularity is achieved by using a certain type of design method to redesign the product to create new product family.

Modular product design refers to designing products, components, and assemblies that satisfy various functions through the configuration of distinct building blocks. Erlandsson *et al*, (1992) conducted a study on seven companies, and the results indicated that increase modularity of a product gives positive effects on information and material flow in a company, from development and purchasing to storage and delivery. Some the issues associated with modular design include:

1- Interface evaluation and analysis
2- Module creation and identification
3- Module selection and configuration to achieve optimum synthesis
4- Quality and field warranty

5- Loss in product identity
6- Compliance to environmental regulation changes.

Nevertheless, modularity advantages and benefits are enormous; it supports mass customization, makes the design more flexible, and eases the management of product architecture (Stone *et al*. 2000). Tseng (2008) examined the impact of collaborative design platform and identified the missing link between customization and collaboration. Without any doubt, modularity contributes in companies' strategic decisions by understanding the interaction between components, modules, and sub-systems. Contribution comes from outsourcing decision of modules, components, or technology in the early design stages. Other advantages are pointed by ElMaraghy (2009), promote the rapid exchange of components, rapid introduction of new technologies, facilitate outsourcing and encourage more flexible allocation for production facilities locally and globally.

Three optimization issues are counted toward the disadvantage of modularity design as Fujita and Yoshida (2004):

1) Optimize module combination under predefined module candidates attributes

2) Optimize module attributes under fixed module combinations

3) Optimize both module combination and module attributes simultaneously.

2.3.1 Modular Architectures

A simple definition for modular architecture was presented by Mikkola (2000) as an arrangement of functional elements in building blocks and can be developed by defining a mapping of physical and functional elements considering interface specifications between components or modules. Products architecture defines the functions of its components and the topology of their interfaces (AlGeddawy, 2013).

Modules' interfaces provide functionality to the product and easily adopt or eliminate a group of function from the product architecture. In addition, product architectures facilitate further detailed design, testing, and planning of its manufacture and material supply chain of those components (Ulrich, 2012). Modular architecture is an efficient methodology to increase design flexibility, manufacturing flexibility, and reduce design process complexity.

An illustration of the depth of the architecture hierarchy of components, modules and subassemblies defines its level of detailed description or granularity as introduced by (AlGeddawy, 2012) in figure 2.6; it has important implications on all subsequent activities throughout the product life cycle

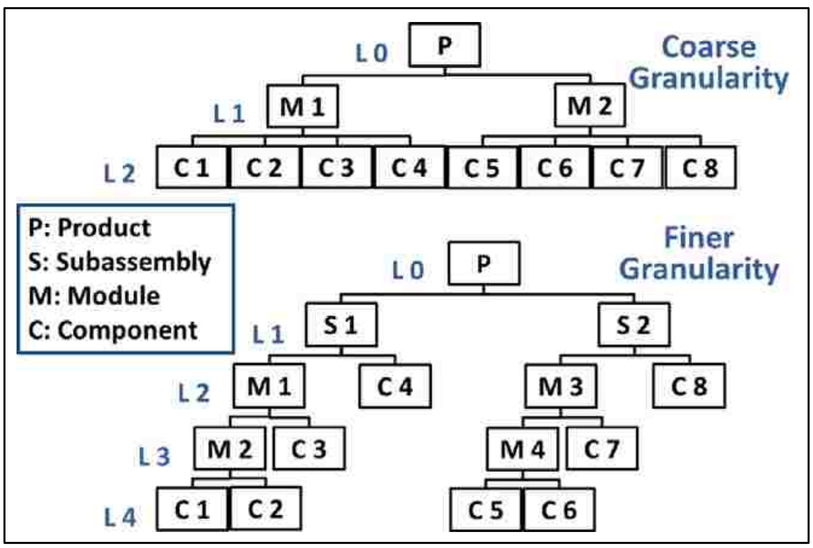

Figure 2.6: Different Levels of Product Architecture Granularity (AlGeddawy, 2012)

By analyzing the modular architecture, designers have the ability to find common and different components to change functions between products. Ulrich is a well know researcher in the modular architecture development, and he developed a four-step process to establish the modular product architecture:

1. Create a scheme of the product by developing a conceptual modules of components and functions
2. Cluster the elements of the scheme by grouping components inside of the modules

3. Create a geometrical layout of the design to detect interfaces and modules
4. Identify fundamental interactions in the scheme and relationships between modules help to assign groups of designer to be in charge for the modules (Ulrich, 2000)

2.3.2 Modular Measures

The first impression to understand modular complexity is the number of components or design difficulty; but in reality, complexity of modularity is the number of type of relations and elements in a product. Measuring the modularity of a product is a tough task to define precisely. Many measures have been developed and several researches have been conducted in the past years. The latest research was conducted by a group of researchers, engineers, product development managers, and independent students to evaluate the degree of modularity using ten consumer products. The outcomes were statistically insignificant and there was no agreement on what product was more modular than another. Furthermore, one of the most important researches was conducted by Guo and Gershenson (2003), to find the best modular measure from a variety of product modularity by extracting the conceptual similarities and sensitivities. Most measures deal with physical components, but very few are extended to the design phase to replace the components with functions. Some metrics are designed for particular applications such as supply chain management or recycling, and others to calculate the degree of modularity in terms of connectivity. Metrics based on the connectivity of modules are more appropriate in developing independent modules

2.4 Product Design and Variations

Product variant is defined as a type of product belonging to a product family (De Lit, 2003). The globalization and uncertainty of market demand in the automotive industry forced manufacturers to increase product diversification and customization. Both product diversification and customization are very crucial elements in any industry to fulfill customer needs and achieve satisfaction. Variations exist regardless of the complexity of the products and can be created during the time of sales or use (Hu, 2011). Product variation might be as simple as a chrome-plated bolt or as complex as an entire vehicle. In other words, variations happen by changing or replacing a module, a component, or even a small part. Unsystematic approach to offer a wide range of product variants leads to a considerable expansion in the number of stocked raw material and sub-assemblies (Bragg, 2004). The number of varieties offered by manufacturers has increased significantly over the last decades. Product variety creates both challenges and opportunities for firms (ElMaraghy, 2013) as customers prefer broad product lines. Therefore, marketing managers are rewarded with greater revenue when they increase product variety. However, this may also increase costs and reduce profits (Johnson, 2009) along with challenges on logistics performance (De Groote, 2011), and erosion in profitability along with higher prices for the consumer (Roy, 2011). Too much differentiation hurts both retailers and the manufacturer (Rajagopalan, 2012) unless variety is well-controlled in all phases of planning, design, manufacturing, distribution, and dismantling.

Several researchers proposed different models and methodologies to manage variation at design and manufacturing levels, yet maintain profitability while reducing development cost and managing product complexity. On manufacturing system level, the broad selection of variations forced manufacturing systems to be more flexible and move from mass production to mass customization. Where on supply chain management, more software vendors responded to the challenge by developing various solutions, such as production configuration (PC) system, systems and customer relationship management (CRM), and product data management (PDM). Existing of several softwares added the risks of selecting the appropriate and suitable system for an enterprise. (Forza, 2008) proposed a conceptualization model by identifying software functions and cross references the relationship between them. The shift in manufacturing requires a significant amount of investments in the manufacturing systems, especially when manufacturers offer variations with very low volume and demand. Low volume production essentially reduces profit and increase complexity management. Special tooling and needed to make unique parts, and the scale of economy is defeated at this point.

Variation-oriented data structures and planning methodologies was introduced by (ElMaraghy, 2009) to link product design to manufacturing process by demonstrating the propagation variations of part/product in a hierarchy format. The methodology captured the degree of variations and commonalities between parts to manage batch production more efficiently. However, optimizing the manufacturing system to improve batch production efficiency is one thing, and understanding the necessity of product variations to market demand another thing. The approach did not evaluate the necessity of variations and market needs, but rather worked around it from manufacture system perspective.

Several attempts were proposed to work around the available product variations by delaying the line-of-differentiation point in the assembly plants as much as possible. Delaying Product Differentiation (DPD) can reduce manufacturing complexities as proposed by AlGeddawy (2001) by optimization the assembly layout to delay the differentiation line. The optimization employed Cladistics tool to manage complexity and minimize duplication of maximizing system utilization. Another approach is to design an efficient and effective assembly system and operation (Hu, 2011) to accommodate product varieties. As proposed by Hu, variety can be achieved at different stages of product realization, design, fabrication, and sales. Complexity review of product design process, manufacturing, and business was analyzed (ElMaraghy, 2012) to propose complexity modeling and management approach. The approach encouraged companies to adopt flexible technical solution and effectively innovate and manage complex socio-technical systems. The drivers and source of manufacturing complexity, as illustrated in figure 2.6, are identified and classified as 1) hard enablers, 2) soft enablers.

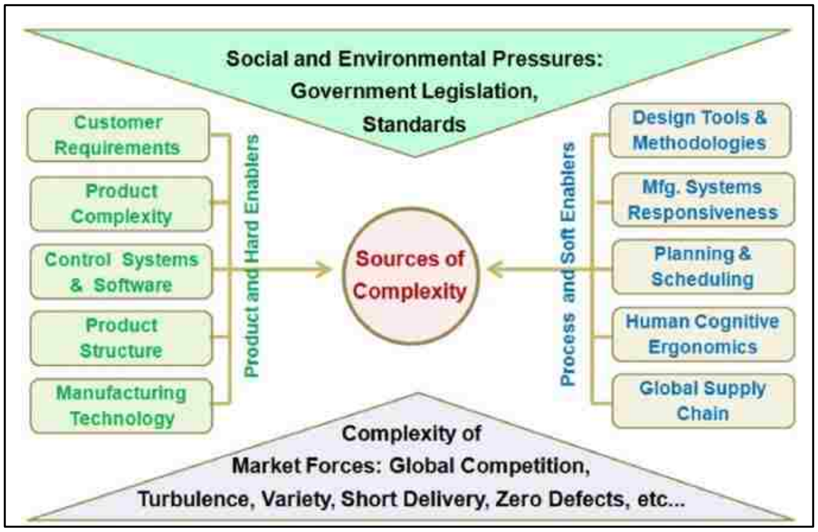

Figure 2.7: Drivers of Manufacturing Complexity (ElMaraghy, 2012)

2.5 Product Complexity

There is no formal and universal definition for the word "complexity", (ElMaraghy, 2012), and the word complexity defines itself as the opposite side of simplicity. Oxford dictionary defines complexity as something that is made of (usually several) closely connected parts. In other words, the more connection and components exist in a system, the more complex the system is (ElMaraghy, 2012). Apparently, everyone agrees on the fact that simplicity is better than complexity, and we need simplicity to be considered in all aspects, products design, manufacturing, supply chain, logistics, and even interactions between employees. The easiest way to achieve simplicity is by avoiding complexity. May be this is the simplest way to define complexity. After hundreds of experiments, Walfram (2002) described the phenomenon of increase complexity as:" *"If we see a complicated mechanical device, we normally assume that the plans from which the device was built must also somehow be correspondingly complicated. But the results [of experiments] show that at least sometimes such an assumption can be completely wrong".* According to Maeda (2013), in his book "The Ten Laws of Simplicity Stated: establishing a feeling of simplicity in design requires making complexity consciously available in some explicit forms. Therefore, simplicity needs complexity to stand out. The more complex is the background in design, the more simplicity pop out in comparison.

Exponential increase in complexity overtime continues to be one of the biggest challenges in the automotive and manufacturing industries. With the mass production strategy in the automotive industry, companies attempts to use Henry Ford's zero complexity approach to eliminate real and perceived complexities.

Competitive pressure and market demand drive rapid increase in product variety. These two factors classify complexity-management as a significant problem in the automotive industry. To meet unpredicted customer behavior and demand, product variants of several thousand configurations are very common. The impact of such high levels of product variety is difficult to assess, manage, or control, and potentially leads to ever increasing process complexity in product introduction and supply. Complexity exists on all levels including, manufacturing, design, supply chain, customer, process, and even on company structure level. Nowadays with new technologies, the required Bill of Material to build a vehicle has been increased significantly, which increased the complexity level of products on various levels, mechanically, electrically, human-machine interface, and on-line to the World Wide Web (Atzori, 2010, ElMaraghy, 2012).

Product complexity creates a variety of direct and indirect related costs, such as the coordination cost to design and cost to production. In the automotive industry, complexity is created by component variations, interactions, and technology. To elaborate more on the main sources of complexity, we can say the sources are:

1- Quantity: A vehicle can be designed with a single to several switches assembled on the instrument panel. Adding a multiplex module in the instrument panel reduces wiring, saves weight, ease packaging, and improve performance. The tradeoff of the multiplex is more drawing releases, more part numbers, more validation and testing, and certifications.
2- Interaction: navigation system is a very useful device for drivers, and requires satellite signals to navigate drivers. However, Radio and other electronic devices work on signals as well. Design packaging becomes more complex with more components added to the IP. Interactions between systems require more complex

design to avoid signal conflict or electromagnetic field issues. Especially, if both the radio and the GPS are integrated together using same screen and signal.

3- Novelty: when a function involves a new technology or a new architecture, there is a lack of know-how of interactions between components. Understanding and the relationship between components creates complex situations. For example, when a new design is proposed to change the frontal facial of the vehicle, it affects the entire vehicle's aerodynamics. Potentially, the gas consumption per mile is change, along with other factors such as vehicle drag and noises. Lengthy design iterations are required to create the desired vehicle performance. The interactions between vehicle performance and facial design should be optimized.

Complexity started to get researchers attentions in the last decode due to the increase amount of modules, components, parts, and features in products. This increase forced manufacturer to study the source of complexity, and how it can be controlled. Uncontrolled complex situations put companies in chaos situations, and become very difficult to control inventory and manufacturing process. This chaos creates an indirect cost and unnecessary expenses which can be eliminated. Enterprises starts to realize the importance of identify sources of potential complex situations, and initiate countermeasure to control and handle them. Therefore, significant studies were conducted on complexity from different perspectives, coupling, variety, design, engineering, configuration, interfaces, and more. To solve complex issues appropriately, they need to be classified and prioritized, and identify the type of complexity. Therefore, researchers were able to identify more than thirty two types.

2.5.1 Complexity Types

There are several types of complexity. Colwell (2005) was able to identify thirty two types in twelve different disciplines and domains, including functional, structural, technical, and operational complexity. Axiomatic Design approach defines complexity as uncertainty in achieving the functional requirement (Suh, 1999). Physical and functional are considered the two fundamental domains of complexity. Physical domain consists of static and dynamic complexity, and functional domain consists of time-independent and time-dependent. Both physical and functional domains are classified by ElMaraghy (2012) as illustrated in figures 2.8 and 2.9 respectively.

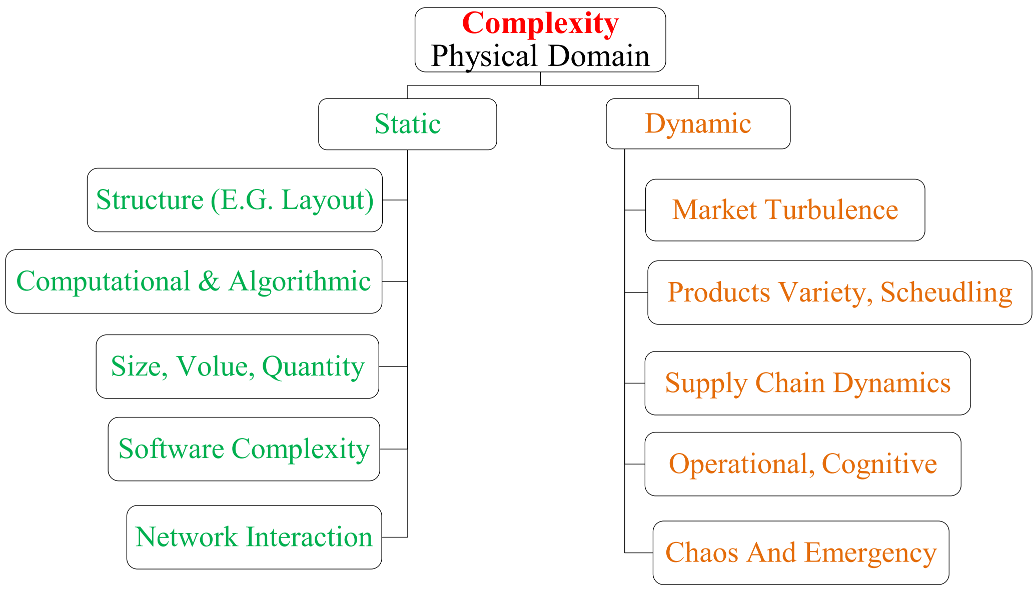

Figure 2.8: Classification of engineering design and manufacturing complexity in the physical domain

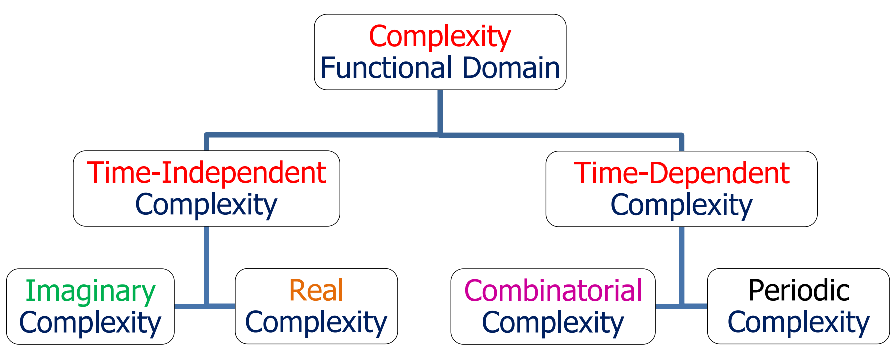

Figure 2.9: Classification of the Various Types of Complexity in the Functional Domain

The amount of information needed to describe the engineering system is a static complexity. Static complexity is time-independent and can reduce and simplify the product design and design process (Frizelle and Woodcock, 1995), and functional and structural complexity of the design process (Braha, 1998).

In contrast, dynamic complexity is time-dependent and is connected to the operational behavior of the system. With consideration of the uncertainty factor, the dynamic complexity can be defined as the expected amount of information needed to describe the state of a system deviating away from its design performance intent. The notion of operators and operands was introduced to describe a design and define the structural complexity by measuring the design size and designing effort. To measure the design size, Braha (1988) considered the total and unique number of operators and operands and measured the size and diversity of information where the design effort is a measure of mental activity to reduce a design problem, and effort is related to the reciprocal of information content. A research conducted by Suh (2005) to reduce the complexity of any system. The theory has been adopted and applied in the design of engineered and manufacturing systems, which suggests that complexity can be defined in the functional domain as a measure of uncertainty in achieving a set of tasks defined by functional requirements. As proposed, complexity can be reduced in any system by taking three actions:

- Minimizing the number of dependencies
- Eliminating the time-independent real complexity and the time-independent imaginary complexity
- Transforming a system with time-dependent combinatorial complexity into one with time-dependent periodic complexity by introducing functional periodicity and by reinitializing the system at the beginning of each period.

2.5.2 Complexity in Design

Complexity is a natural step of creation for new designs, and is the function (Colwell, 2005) of all ideas storming in the head simultaneously. Any new design starts with massive number of ideas generated by brainstorming or concurring engineering methods. The more generated ideas toward a new design, the more chaos they generate. Increasing the number of ideas lead to complex situations. Researchers proposed numbers of methodologies and theories to reduce complexity in design. The design for assembly (DFA) method generally suggests a reduction in the number of parts, with the possible result of increasing shape complexity of resulting composite parts. The trade-off of this method is reduction in part quantity and increase complexity in manufacturing systems. Design's complexity must serve a project's major goal. Complexity can potentially be avoided be eliminating unintended interaction among multiple unrelated design decision. Axiom design approach toward design complexity has been adopted by several researchers. Kim (2004) proposed four causalities: coupling, uncertainty, difficulty, and non-equilibrium. Some researchers argue that engineering should be reducing the system complexity to make the design more robust, where others disagree with this approach and encourage engineer to adopt complexity to be more creative (Eijnatten, 2007).

Few steps need to be taken in the design phase to come up with the ultimate design:

- Cluster differences and similarities to identify relationship between inputs
- Remove irrelevant ideas.
- Add and generate ideas in empty areas
- Navigate between groups to identify logic relationship between them
- Define function roles to understand the structure.

Mingasson (2011) presented a very basic visual illustration to the relationship between simplicity and complexity in design, and how new ideas are generated starting from inputs with chaos, to the final and simple design

Other researchers identify the relationship between complexity, chaos and complicatedness and classified chaos as an escalated stage of simplicity with an increase of design requirements. (ElMaraghy, 2012) demonstrates the spectrum of process complexity and the relationships between requirements, technology, and robust tools, as illustrated in figure 2.11.

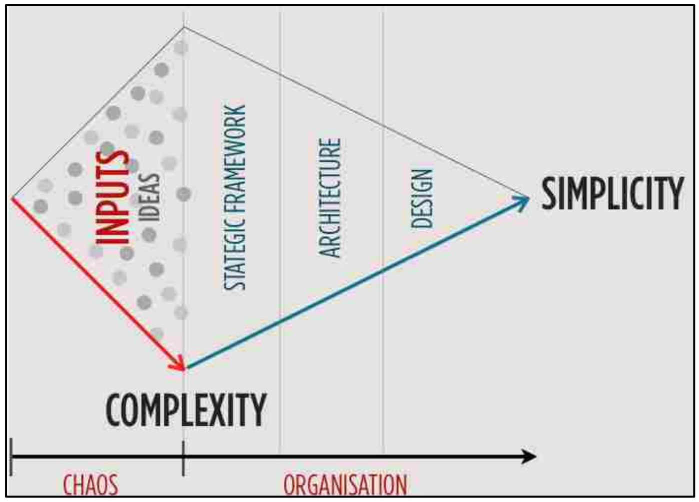

Figure 2.10: Relationship Between Simplicity and Complexity In Design (Mingasson, 2010)

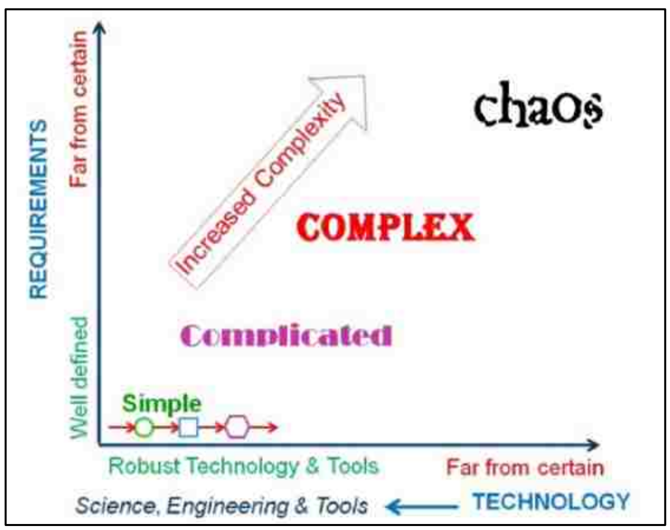

Figure 2.11: The Spectrum of Process Complexity (ElMaraghy, 2012)

Understanding and resolving complexity of new design in the design stage is very crucial to generate a robust product and independent modules which can operate independently. Typically, it is very hard to balance between design and manufacturing complexity. Most often, design engineers design products per customer requirements, and let the manufacturing engineers to handle the manufacturing complexity aspects. Maybe is this not the proper way to handle business, but it is a reality in the manufacturing world. Therefore, all departments should participate in any new designs to avoid unforeseen complexity, as well to be prepared for unpredicted situations.

2.5.3 Complexity in Produce Development Process

On-going investment in research and product development enables companies to be more responsive to the market with new technological products. New products with higher quality design give much better returns to shareholders and economy. As a result, companies will be capable to manage complex product development and manufacturing which will ultimately lead the enterprise to have a definite competitive edge. The quantity of product variants requires diversified process, which increased the complexity in the product development process. Therefore, managing and controlling product complexity became an important issue in the automotive industry. Some OEMs experienced bad product quality, and were forced to recall several products due to lack of controlling the product development process.

Desing process was describe by Summers and Shah (2010) as an iterative problem solving process in which the designers typically externalize the design problem, process, and product. The function requirements of a design can be satisfied by finding solution from adopting a design process of a proposed model. The design process may include procedures, regulations, best-practice, and experience. Managing design and complexity has been researched by several researches, and different models and paradigms were proposed to manage complexity. Lu et al. (2007) proposed a paradigm to manage design complexity through collaborative efforts in developing scientific guidelines for Engineering as Collaborative Negotiation (ECN) based on research hypothesis. Figure 2.12 illustrates the Nature of Knowledge and Decisions in Collaborative Engineering. Collaborative engineering is the application of collaboration sciences to the engineering domain to accomplish complex technical tasks, which is the challenge currently faced by the engineering community including industry.

Other researchers Tichkiewitch (2011) and Pimapunsri (2005) consider the problems to design and develop a product are not complex, but to find the appropriate solutions for the problems could be either complex or noncomplex. However, the proposed method was presented to design process for non-complex products by using integrated design. ElMaraghy (2012) proposed a unique approach to define complexity in the design process and product. The approach identified three aspects to complexity: size, coupling and solvability, which are all referenced to parametric and geometric problems for “embodiment” design.

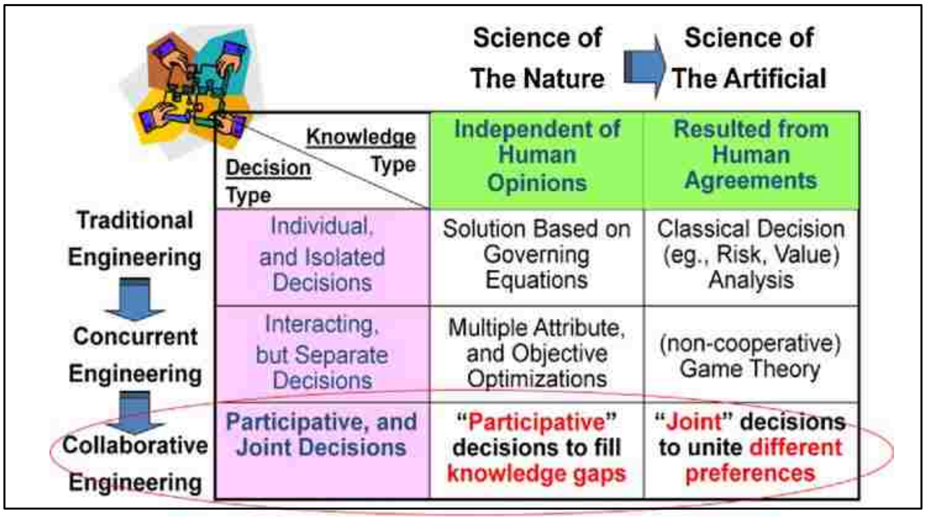

Figure 2.12: The Nature of Knowledge and Decisions in Collaborative engineering (Lu et al., 2007)

Understanding the product structure and the interaction between components help to control complexity rather than reducing it. An effective system for controlling complexity permits the prediction of change impact that previously would have gone unnoticed (Lindemann, 2009). To manage complexity in product development, engineers should understand all types and potential sources of complexity to develop an appropriate metrics. Methodologies such: An Inventive Problem Solving (TRIZ) (Justel, 2006), Design for Manufacturing (DFM) (Rodriguez-Toro, 2004), and Engineering Collaborative Negotiation (ECN) paradigms

As some researchers think complexity is not complex if the source is known. Other researchers (Lu 2007, and Deshmukh 1993) proved by conducting manufacturing benchmarking that complexity brings profit to the organization. This condition is satisfactory if manufacturers master complex situations. ElMaraghy (2008) extended Zachman (2008) enterprise architecture framework for software deployment, and proposed a holistic architecture and framework for complex products from creativity to final design detailing.

The debate to define complexity preciously continuous as several mathematical models and frameworks were presented by researchers. Complexity is relative term and what could be complex for someone, it could be simple for others. When potential sources of complexity are identified, and the design and manufacturing process are defined and followed, complex situations can be simplified.

2.5.4 Complexity in Manufacturing

As complexity was considered and discussed in product design and development, it has been studied on manufacturing process level. Manufacturing engineers need to understand complexity in manufacturing of complex parts, in process, assembly, and combinatorial cost associated to product variations. The uncertainty in market demand, along with manufacturing complexity, the more challenging complexity in manufacturing industry is the manufacturing systems; which forced companies to understand and adopt complexity on their manufacturing systems level (ElMaraghy 2009, Koren 2010).

Several methods have been adopted to evaluate the manufacturing index to enable simple and alternative designs. Design for Assembly (DFA) method, which demonstrated a proven record of successes by suggesting a reduction in the number parts in a system. Ultimately, the cost of manufacturing is associated with the number of manufacturing process required to produce a complex part. The axiomatic approach for system design has been investigated by researchers for Nano-Engineering applications to develop less complex manufacturing process (Kim, 2006). The approach studies the manufacturing process on micro-scale level to simplify complexity. Design for Manufacturing (DFM) (Poli, 2001) is another method to be adopted to reduce cost and complexity of manufacturing.

Other researchers (Chryssolouris 1988, Dornfeld 1990, Monostori 2003) proposed more techniques such as the machine learning techniques for managing complexity and uncertainties in manufacturing process, artificial intelligence, and neural network. Manufacturing and controlling senses were added to the manufacturing process to monitor assembly specifications and requirements. This constant monitoring process simplifies the manufacturing process complexity to some extent. Different signals to control the process can enhance the control performance.

Complexity in manufacturing system is even more complex than the manufacturing complexity itself. The uncertainty in the global market made increased manufacturing system complexity. Manufacturing systems should be ready at any time to manufacture any complex product or design with least investment cost. Increase of product varieties generate more information, which need to be processed. Not to mention the needs to manufacture out-of-boundaries and unexpected products to meet personalization strategy. Unexpected products to the controlled process increase the effort to operate and manage consequences. Recent manufacturing systems have been evolved dramatically in the last decade to accommodate product variations on production planning and process planning.

Complexity in manufacturing systems comes from the number of required machines, tools, equipment, operators, and the interactions between human and machines. Automated machines influence complexity when more sensors are added to the process to reduce physical work and human error. Another source of complexity to the manufacturing system is the machine layout and manufacturing sequence. Complex products require more work, which leads to more cost in manufacturing and process systems. Therefore, the two types of complexity mentioned earlier apply to the manufacturing system.

Sometimes, manufacturing complexity cannot be predicted in the early stage, especially if the part topology and geometry is new. At this point, manufacturing complexity can be estimate analytically (Lue, 2010) to calculate a manufacturing index by using similar products. Complexity in design recommends reducing the number of parts despite increasing shape complexity. However, the cost of manufacturing is related to the number of operations and tools needed to manufacture a part. If design proposed complex shape to reduce complexity, manufacturing cost goes up along with increasing the manufacturing complexity.

Several theories and ideas proposed by researchers to control and reduce complexity in the manufacturing system. Complexity of a system can be treated by utilizing cybernetics and feedback control (Peklenik, 2003). The system was divided into Elementary Work Systems (EWS) by applying the concepts of control and information theory to control the production process. A methodology used in software engineering was adopted by Schuh (2004) to manage complexity increase in the automotive systems. The discrete event simulation and nonlinear dynamic theory used by Papakostas (2009) to investigate the stability for the complex manufacturing system, and determine the sensitivity of a manufacturing system to workload change and measure its complexity. ElMaraghy (2004) proposed a framework and matrix methodology with consideration of on several realistic factors in the manufacturing environment: information, diversity, content, quantity, product complexity, and operational complexity. The proposed model assesses the complexity on three levels: product complexity, operational complexity, and process complexity.

2.5.5 Complexity and Product Modularity

The modularity concept and product platform have been identified as effective strategies to offset some of the increasing complexity in the frequent change era. For product and process modularization, the elements of their design are split up to modules according the architecture or plan. The idea of modularization makes complexity more manageable, enable parallel work, and accommodate present and future uncertainty. Modularity concept has a big benefit to reduce present uncertainty, and fast response to future uncertainty. The quick response to market demand is reached by a quick replacement of modules, which is assembled as customer needs change rapidly. However, module complexity comes from the unforeseen interactions between new and current modules. Modularity has the power to change the structure of an industry, and Baldwin and Clark (2006) showed the power. Parker (2010) studied the relationship between modularity and complexity and showed that complexity can be reduced if interface between modules can be managed, and the product modularity associated with the complexity of internal manufacturing processes and supply network in situations of high outsourcing and high environmental uncertainty.

Modularity concept enables the mass customization model, which has been around for a long time. Mass customization promotes the provision of personalized products with respect to economy of mass production. By agreement, operation complexity arises from the massive number of product variants, and modularization is recommended by Brun and Zorzini (2009) to control complex operations or sometimes even reduced.

2.5.6 Complexity by Variety

Product variation stimulates product complexity due to the increase number of functions, modules, features, and variants. While it is desirable to fulfill the needs for variety which might increase cost of some systems as a result of complexity, it cannot be achieved at any cost. The relationship between complexity and cost is always in a dynamic mode. Modular product and process design can reduce complexity and cost. However, it is extremely important to differentiate between the complexity and variety effect on the final cost (Roy, 2011). The challenge is to respond quickly to the dynamic shifts in customer needs and increasing complexity due to variety and the balance between personalize and quantity-driven mass production. Figure 2.13 clearly illustrates the dilemma of production scale versus scope, which is intensified by today's increase in product variety leading to a flattened curve of production quantities to include highly individualized products (Suh, 2005).

From marketing managers' perspectives, product variants are necessary to offer and meet any customer expectations. The consequential profit is often overestimated and does not compensate for the complexity-induced costs which cannot be easily quantified by traditional cost-accounting methods (Cooper, 1993). In contrast, standard products with high price to subsidize personalized products reduce competitiveness. According to complex system theory (Johnson, 2008), A complex system exhibits two complementary characteristics, an increased plurality and variety of elements as well as a high degree of interdependence and dynamics between elements

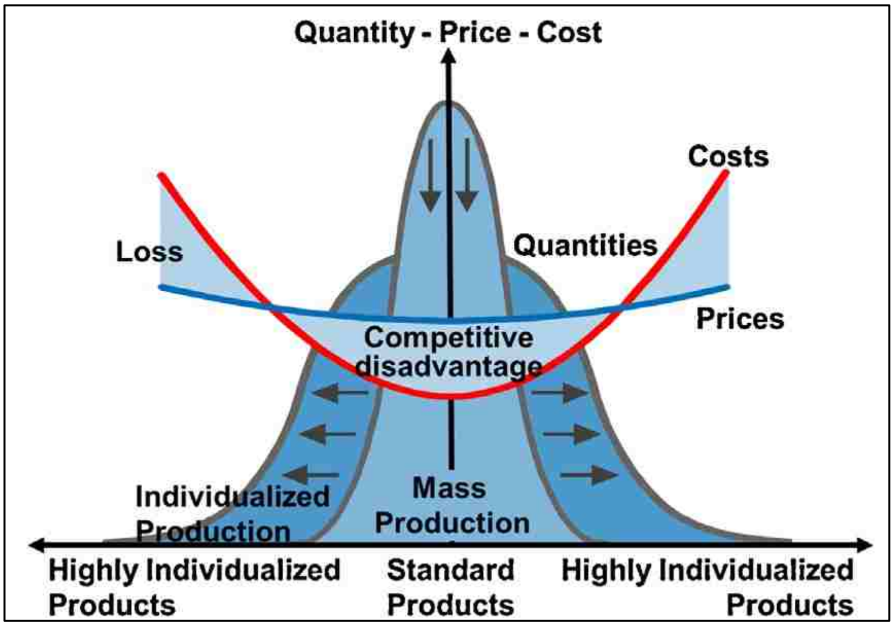

Figure 2.13: Typical Cost/Price-distribution in Individualized Production (Source: Schuh, 2007)

Overall, variety is what the market and customers expect in the product functions. However complexity that results from variety is related to complexity of the product due to the large number of variants and the resulting operational complexity as well as complexity of the manufacturing process that is capable of effectively producing all of these variants. Modern complex products or equipment may have many thousands of parts and take hundreds of manufacturing and assembly steps to be produced. The complexity increases with the number of variants, as well as the presence of ''multi-disciplinary complexity'' as most products and equipment now incorporate not only mechanical and electrical components but also software, control modules, and human–machine interfaces (ElMaraghy, 2012).

2.6 Function and Functions Attributes

Design process and designers exist to create a product that satisfies customers and some purpose of function. Knowledge of functions and their purposes is very crucial to design-related activities; activities include modification of design, comparison, evaluation, feature selection, and comparison of designs. By agreement among researchers, functions determine a product's fundamental characteristics. Yet, there is no clear and widely accepted definition of functionality. Historically, function was defined by Umeda and Tomiyama (1997) as an abstraction of the intended behavior of design and a relationship between a design and its environment. Interpretation of function has been influenced by design methodologies used in the design process. Designers identify functions by initiation product specifications and requirements. Functions typically can be branched into sub-functions or function attributes, which is a process to create and assign values to create functional structure. Mile's definition of function has primarily been used in Value Engineering (VE) work by representing function I the form of "to do something" and by comparing the value of function with respect to the costs of the product.

There are several approaches to represent functions in design, such as:

1. Representing function in the form of pairs or more (Miles, 1996). A function of a shaft is to transmit power and speed.
2. Input and output flow transformation, where inputs and outputs are Materials, information, and energy. Figure 2.4
3. Transformation between input-output situations and states.

Inputs and outputs between the second and third approaches are different. To explain the difference further; a household buzzer, according to approach three the function is "make a sound" which can be represented by two behaviors:

1- Representing an upward clapper movement,
2- Representing a downward clapper movement (Goel and Stroulia, 1996).

Relationship and correlation between functions and product prices was proposed by Petrin and Trian (2003), the approach based on control functions. The basic idea is to include extra variables in the estimation equation that condition out the part of the error that is correlated with the repressors. Thus, the concept dates back at least to Heckman and Hausman (1978). Petrin implemented it in a discrete choice environment where price endogeneity often raises econometric concerns. The approach is a general approach to price products based on supply and demand, with full ignorance to market shares and size of an enterprise in relationship to global market competition.

There are several types of functional models. Function Behavior State (FBS) proposed by (Umeda *et al*. 1996). Umeda considered the output of the functions is a behavior, as mentioned in the buzzer example previously. A second type of function model was proposed by Geol and Stroulia (1996), Structural Behavior Model (SBM). Stoulia considered the process of the electricity flow and destruction of the magnetic field is the buzzer is an internal behavior. FBS model emphasize the representation of the output behaviors of a system or component. This model is used in this dissertation to measure and evaluate function outputs through functions attribute value.

Function, can be generally defined as an intuitive concept which purely depends on the designer's intention, which strictly established to serve a specific need and fulfill customer expectations. This general definition is adopted in this research to define the structure of each function by its function attributes and values.

2.7 Product Platform and Product Family

The goal of product platform strategy is provide the enterprise with flexible and common modules to produce customized product family variants with the least product family complexity and development, maintenance cost, and production while maintain flexibility to customer demand and technology change.

Sharing common modules and components across platforms and families; enterprises can save money and offer wide range of variety for products through economies of scale. However, there are some drawbacks and concerns toward this strategy, as we will discuss in more details in the following sections.

The concept of product family, product platform, product derivatives, and platform architecture are not new. Product variations of automotive products consist of eight distinguished levels as presented by ElMaraghy (2009). The hierarchy clearly identifies and clarifies the relationship between product platform, product family, and products within an enterprise, or portfolio as illustrated in Figure 2.12.

2.8 Product Platform

Various definitions of the product platform have been proposed by academia researchers and industry experts. The basic definition of platform is the use of standard modules between different products. A collection of parts and product variants design shared by product families generates product platforms (ElMaraghy, 2013). It has been identified that the product platform approach is used in the automotive industry to reduce production cost by maximizing commonalities and utilize economies of scale between different product families (Sue, 2005). The product platform is generated by sharing product families on components level. However, this dissertation refers to product families as a group of product platforms. Meyer (1997) defined product platform as a set of common components, modules, or parts from which a stream of derivative product can be efficiently created and launched. The major implication of platforms is using common manufacturing process, technology, and knowledge which are shared by multiple products in a family. Simpson (2004) has a different view on platform definition; platforms are used to create individual products either by addition/ substituting/ subtracting of one or more modules or by stretching one or more design variable.

Simpson et al. (2001) define product platforms as a set of parameters, features and/or components that remain constant from precut to product within a given product family. However, features, components, and parameters do not have to remain constant within the same products family, especially by stretching one or more design variable as defined by Simpson (2004). In addition, parameters and components can be applied across different product families, not only within the same family, as we will demonstrate later on. Simpson takes into account that platforms can be either module or scale based

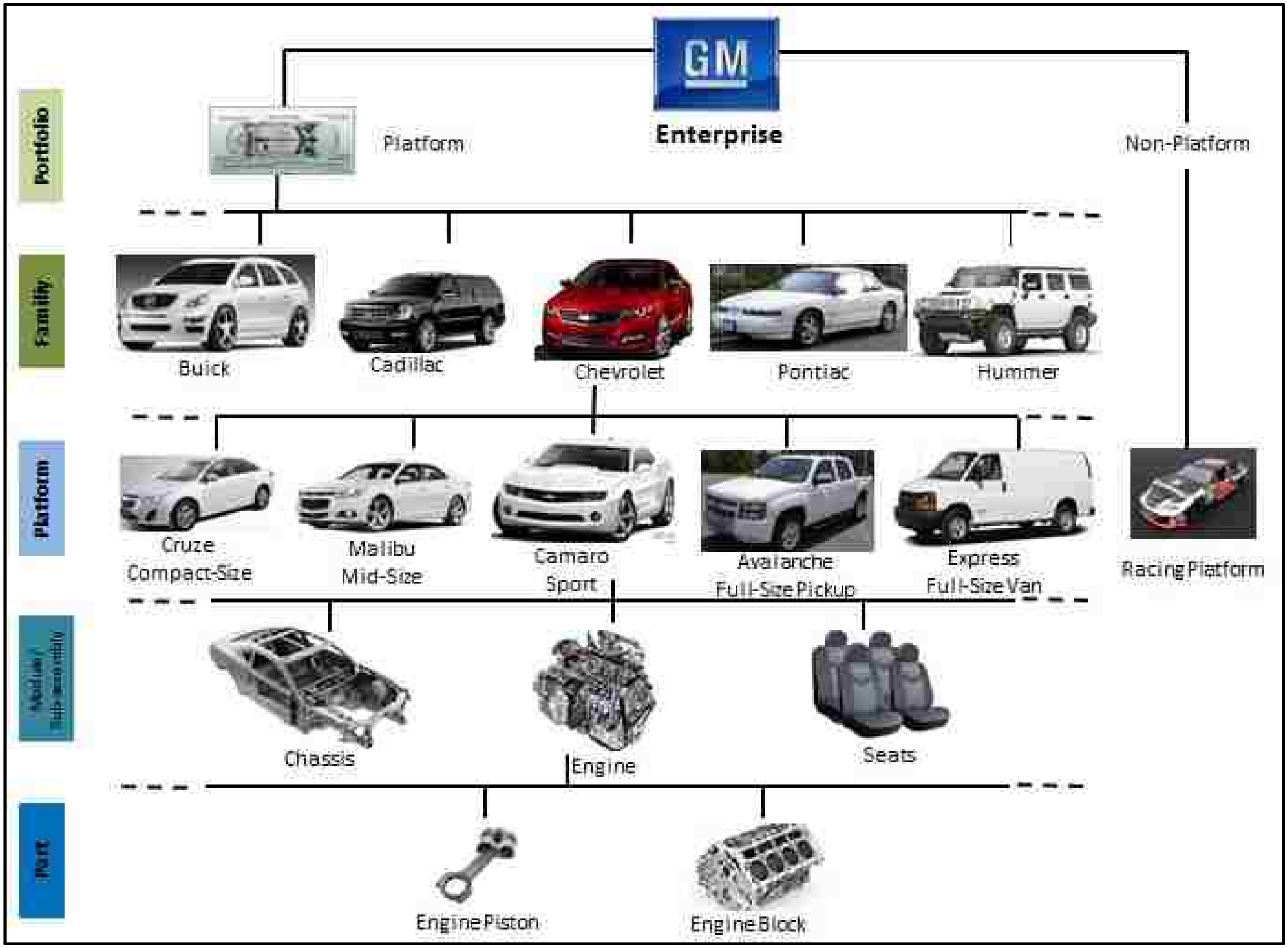

Figure 2.14: Product Variety Hierarchy in Automotive Industry (Reference to ElMaraghy, 2009)

2.8.1 Product Platform Advantages and Disadvantages

Robertson and Ulrich (1998) point out the benefit of the product platform strategy and stated “by sharing components and production process across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing process, and take market shares away from competitors that develop only product at a time.” One of the most and obvious benefit is the cost saving from economies of scale by sharing common components across the product family. Cost saving resulted from designing and validating less modules and assemblies as called in the industry terminology piggy-bag or surrogate validation data. Cost saving applies on manufacturing systems layout and supply chain process. Another advantage is reallocating available resources and budgets gained from commonality toward researches and new concept development.

Benefits on the design level are massive. Standardizing design processes leads to reduction in design development lead time and cost by implementing lesson learned, applying systematic design process, and applying and know-now knowledge. Flexibility and responsiveness in the manufacturing process is a crucial advantage in the manufacturing environment. More benefits include reducing in production complexity, cost, assembly validation, and line transfer flexibility between different plants (Piller and Tseng, 2010)

Nevertheless, platforms and product families can be used as a tool to accelerate new product development since developing a derivative products based on a platform is faster than developing complete new products. Today, automotive companies are adopting the platform strategies and claiming that they have been successful in shortening the lead time to develop new products based on existing platforms.

Despite the benefits offered by the product platforms, platform strategy has some drawbacks as well. One of the foremost drawbacks is loss of distinctiveness of products due to lack of product customization. Potentially loss of market share is the result. Applying common modules across the product family reflect a bad image when consumers are aware of extensive component sharing between high end and low end products (Cook, 1997). Ford lost some market shares to Mercury which is the lower brand and price vehicle. Ford implemented several identical features and modules in two different families-Ford and Mercury-on several platforms, Midsize and Large size vehicles. Another drawback is module interfaces. Interfaces and compatibility between modules creates some serious quality and performance issues in the field. Especially with the controlled-by-wire technology as electromagnetic fields and interferences between modules could happen. Toyota experienced a serious field safety and quality issues when vehicles became uncontrollable. The Electronic Throttle Control (ETC) and drive-by-wire technology worked on one platform but not on the others and caused interference problems.

This being said, a list of metrics have been introduce by researchers such as Meyer and Lehnerd (2000). The proposed metrics are based on the business performance of the platform and the cost of developing it. Kirshnan and Buptoa's opinion was that the platform development costs are very small compared to the life-cycle cost.

2.8.2 Product Platform Design Methods

Different researchers proposed different platform designs. Product platform design method based on an axiomatic design (Xzie, 2003), Kuang (2008) presents a new product platform design for a product family based on Kansi engineering. Kuang suggest that customer's affective needs should be taken into account by identifying platform and individual parameters, quantify the relationship between product's perceptual image and design parameters, and finally, establish a quantified relationship between average preference and individual parameters for each cluster. Axiomatic design and design relationship is an approach presented by group of researchers (Renbin, *et.al*, 2008). Renbin Considered the link between customer needs and product quality characteristics. Product functional requirements were classified into basic functional requirements, expectable functional requirements and adjunctive functional requirements based on

Kano model, and their concepts are defined. The functional requirements are zigzagging mapping to design parameters. The design relationship matrix was built by analyzing the fluency relationship between functional requirement and design parameter, and the extension clustering algorithm is utilized to cluster the elements in design relationship matrix. Product platforms parameters were identified by analyzing sensitivity of the design parameter, and the clustering algorithm was applied to determine the sharing strategy of platform parameters. Simpson et al. identified two methods: 1) top-down and 2) bottom-up. A top-down approach is more business oriented, and the second method is more technical. The other two main approaches for platform-based product development are module-based product family design and scale-based product family design.

Module-based platforms are product platforms in which products share common modules, but may have different functionalities. The product family members are produced by adding, substituting, and/or removing one or more functional modules from the platform (Martin and Ishii, 2002, Zacharias and Yassine, 2008, and Chen et al., 2009). The module-based platform design problem can be formulated as an optimization problem and aims for an optimum degree of commonality and optimum settings for the platform modules.

Scale-based platforms, on the other hand, are product platforms where products share the same functionalities but are at different performance levels. In the development of a scale-based product family, one or more scaling variables are used to "stretch" or "shrink" the platform in one or more dimensions to satisfy a variety of market niches (Gonzalez-Zugasti et al., 2000, Fujita and Yoshida, 2004, and Zhihuang and Scott, 2006).

The most recent research in product platform design proposed by AlGeddawy and ElMaraghy (2012), ElMaraghy (2013) which suggests a Reactive Product Platform Design (RPPD) using physical commonality, not commonality indices, to automatically generate better variants design alternatives for the product family. The proposed design model offers an innovative mathematical redesign formulation and algorithm for application to groups of product variants, which based on the automatic generation of design platform and modules using Cladistics to produce cladograms, binary tree graph representations showing how different product variants can be grouped based on the commonality and differentiation of their parts and components. Hanafy (2013) proposed a (DPPD) Dynamic Products Platforms Design Model for product platforms by combining different concepts into one holistic model by employing an innovative concept of a changeable module platform configuration. The changeable modules are designed at differentiation line in the manufacturing system by adding or removing some modules to meet fluctuated customer demand. The proposed DPPD model discusses cost associated to manufacturing by adding or removing modules outside of the mass production assembly line – manual operation. DPPD works around the existing product platforms in the manufacturing system without recommending adding or deleting platforms based on market demand and market share.

2.8.2.1 Scale-Based Platform Method

All product variants share the same variables, some of which have fixed values and some of which are scaled; as opposed to module-based product family design, in which complete modules are added or deleted to make unique products. Various product performance levels can be maintained by scale-based designs, while diversified product functions can be offered by module-based designs method. Scale-Based method is simply performed by stretching or shrinking the product platform in one or more dimensions to satisfy market niche with more variety (Zhihuang and Scott, 2006).

A new method was established by Simpson et al. called the Product Platform Concept Exploration Method (PPCEM), by using Decision Support Problem (DSP) to design a platform to maximize commonality and minimize performance loss. Messac et al. (2000) started with the assumption that common platform components are identified and then parameters are created, where Simpson started with the market segment grid for his approach. Both researchers utilized physical programming to formulate the sole robustness problem. Hernandez et al. (2001) proposed the Decision Support Problem (DSP) approach to design a robust product family with the assumption that common products are known. Another researcher, Conner et al. (2002) shows a quantitative method to determine the number of product platforms or common components. Later, Conner added an expected utility of predetermined possible scenarios; each scenario gives a certain probability of occurrence.

The main approach to scale-based platform design is a two-stage approach: in the first stage, the platform is designed by means of identifying platform design parameters and fixing their values for all products. Then, different values of the individual parameters are determined to provide an optimal performance for each individual product in the second stage.

2.8.2.2 Module-Based Platform Method

Module-based platform design or method has been approached by several researchers from different viewpoints. Platform design is essential for successful family design as demonstrated in numerous products in different industries. Simpson et al. (2008) proposed a new Strategic Module-based Platform Design Method (SMPDM) to determine a platform design strategy in a dynamic and uncertain environment. The new design proposal introduced unique modules, common modules, and engineering parameter modules to identify the module based platform design. Moore et al. (1999) use conjoint analysis to determine a product platform. Siddique and Rosen (2000) review the commonalities in the assembly process to describe a new design platform method from an existing set of products. Minimum cost-based objective was the interactive method to optimize platform designs (Gonzalez *et al*., 2000). All the mentioned researchers evaluated the platform after identifying and choosing the platform modules with at least analysis of module functions and influence to the market share.

2.8.2.3 Matrix-Based Platform Method

Matrix-based platform design method is another method to develop the design, and provides the first mathematical attempt to clumping sub-functions of functional models into modules based on quantitative criteria. Matrix-based design methods implement an optimization strategy to manipulate the modularity matrix to achieve maximum modularity by reconfiguring or redesigning the product structural matrix that represents the product architecture. Jujita et al. (2003) introduced a method to utilize Quality Function Deployment (QFD) in product families. Customer requirement weight was not considered in a specific model, but exists in at least one member of a product family to be able to use the same matrix for multiple products in a family. Martin and Ishii (2002) scope was to minimize the connectivity and future redesign of the architecture to develop a QFD based method for platform development. Sudjianto and Otto (2001) used matrix approach to define platform modules based on common functionality. Nevertheless, other researchers designed multi-brand product platforms based on color, schemes, and shape rather than technical attributes.

There are several ways to determining the degree of commonality in a platform. One of the ways was introduced by Fellini et al. (2002), a unique method to choose common components for a platform while optimizing commonality and performance. Fellini's optimizing method decides the number of design variable to share among two products of a family with a known acceptable performance loss.

All previous mentioned design methods reflect decent and respectful academic contribution to design product platforms. Most methods consider the degree to similarity of existing platforms and establish some guidelines for designers to introduce new platform bases on knowledge and experience. The evaluation of current platforms in the market offered by each enterprise is to somewhat ignored. Up to our knowledge, one of the most important assessments to evaluate available variant of models on the same platform and within the same product family has not be acknowledged by researchers. The evaluation determines if one particular platform is over saturated with unneeded models, which potentially causes model cloning. Cloning or redundancy in models which offer identical functions and function-attributes require manufactures to spend unnecessary cost on validation, increase complexity in manufacturing systems, longer supplier chain to manage and control, and most important less revenue and profit. This is the main attention of the dissertation.

Taking a closer look at General Motor compact size vehicle platform, we observe a model named Cobalt which was launched in year 2004. Three years later another model under the same compact-size platform and Chevrolet family was launched, Cruze model. All safety, exterior, interior, mechanical, and power train functions are extremely identical to the 98% similarity. Table 2.1 below gives a quick glance on exterior and interior design differences, very negligible.

Cobalt	Cruze
	
	

Table 2.1: Chevrolet Compact-Size Vehicles Comparison
(Courtesy of General Motors)

Cruze sales volume history was reported by Holmes (2013) and published in Motor Trend magazine, and Cobalt production volume history was reported by Dowdell (2011). A closer look at both production volume and sales, we clearly observe a significant reduction in sales volume on Cobalt as soon as the Cruze model was launched. The Cruze model kept ramping up in sales as Cobalt sales went down by almost 50%. We conclude that the introduction of Cruze to the market was very successful, but the Cobalt model should have been terminated from the market to avoid additional cost, such as manufacturing, supply chain management expenses, marketing, and resources.

	Production Volume Per Model Year								
	2004	2005	2006	2007	2008	2009	2010	2011	2012
Cobalt	4,959	212,667	211,451	200,621	199,045	104,724	97,376	127,472	
Cruze						92,190	225,495	231,732	237,758
Total	4,959	212,667	211,451	200,621	199,045	196,914	322,871	359,204	237,758

Table 2.2: Sales Comparison Between Models

The product platforms have been defined by different researchers, as indicated and mention above, in different terms and approaches. The product platforms for this dissertation will adopt the most common and known definition: (*Product Platform: is achieved by either stretching or shrinking modules, component, and design parameters to achieve new platforms to meet customer demand based on expected function and function attribute to serve and fulfill certain market segments*) (Simpson, 2001). This definition means, a midsize vehicle platform can be modified by stretching modules such as frame, chassis, powertrain, seats, and other components to offer a large size vehicle.

The proposed dissertation methodology along with AlGeddawy and ElMaraghy (2012) design methodology will work hand-in-hand. The combination of both models will assess manufacturers to better evaluate current models and systematically plan and design new platforms and families. AlGeddawy, proposed a design methodology to resolve the conflict between platforms and modularity in product families. The methodology considered the Design for Manufacturing and Assembly (DFMA) which calls for decreasing the number of components encouraging parts integration, utilizing physical commonality.

2.9 Product Family

Product family, known as product line, is a group of related products that are derived from a common set of components, modules, and/or subsystem to satisfy a variety of market applications where the common elements constitute the product platforms (Meyer and Lehnerd, 1997). Each product variant shares some common features and technologies that come from the product platform of the product family (Erens and Verhulst, 1997). Enterprises can efficiently develop a set of differentiated products by sharing and reusing assets such as component, modules, process and ultimately knowledge and information when developing new families (Seung, 2010)

Related products that share some components and or/sub-assemblies satisfy a variety of customer' demand and markets is a definition which was introduced by ElMaraghy (2009). "*A family of products description can vary according to three points of view: 1) Customer or sales; to allow the selection of the desired product parameters' value, 2) Manufacturing; to generate the bill of materials that describes the components and their features and plan their manufacture, and 3) Assemblies; to identify relationships between components and sequence of assembly process. It is informative to capture and classify the hierarchy of product variants, types and scope and consider ways of modeling variety and its effects at different levels*" (ElMaraghy, 2013)

A comprehensive definition of product family can be defined as a collection of knowledge, processes, components, and relationship shared by a group of platforms to offer downstream products for one simple reason, surviving the competitive market with more product variation to dominate the mark share, and less cost to increase probability, with respect to customer needs, responsiveness to the market, and targeted segments. This definition is adopted in the dissertation.

2.9.1 Product Family Advantages and Disadvantages

Enterprises were forced to introduce new product families to compete in the today's global market as they investigate new design strategies to provide a variety of products. Cost effective design essentially can be ranked as one of the most important benefits to bring variety of products to satisfy various customer (Zamirowaski *et.al*, 199). Product family design strategy lowers production costs, and reduces the time taken to introduce new products. Shared components across the family enables designers not only to reduce design cycle time and production costs by improving economies of scale, but also the number of components in production support activities (Robertson, et, al, 1998). Variety and commonality both offer competitive advantage to the manufacturers. Product commonality refers to how well components and functions are shared across a product family, and product variety refers to the diversity for products that a company provides to the market place (Meyer and Lehnerd 1997).

In contrast, shared components in one product potentially have lack of distinctiveness and often exceed the requirements of the products which can incur additional production cost (Krishnan, et al 2001). Consequently, trade-offs involved with product family design needs to be evaluated to avoid additional manufacturing cost, cloning, and redundancy in functions and function attribute to maintain product and brand unique image. Likewise, over saturated product family with wide variety of product increase the difficulties to share functions across the family.

2.9.2 Product Family Design Methods

The most significant challenge in product family design is the sensitive balance and trade-off between product commonality for components shared across the product families and product variations. Product family design, proposals, frameworks, and models have been approached from different perspectives, including the field of marketing, manufacturing, business strategy, engineering, information technology, and management

The design of platform-based product family is an effective and efficient model to offer sufficient product variety to fulfill a range of customer demand in support for mass production. The platform product development approach usually consists of two phases: 1) the creation of the appropriate product platform; and 2) the customization of platform into individual product variants to meet the specific segment market. Figure 2.15 illustrates Volvo family based on truck platform with variation to meet various market segment expectation and federal regulation.

Several models have been presented by researchers to created product families. Roy *el al*. (2011) proposed a model to created product families by utilizing different criteria including modular function deployment for grouping product functions according to styling, technology evolution, planned changes to identify potential product architecture and modules. ElMaraghy (2006, 2007) considered the boundaries of product families are no longer rigid or constant, and proposed a new method named "Evolving parts/products families.

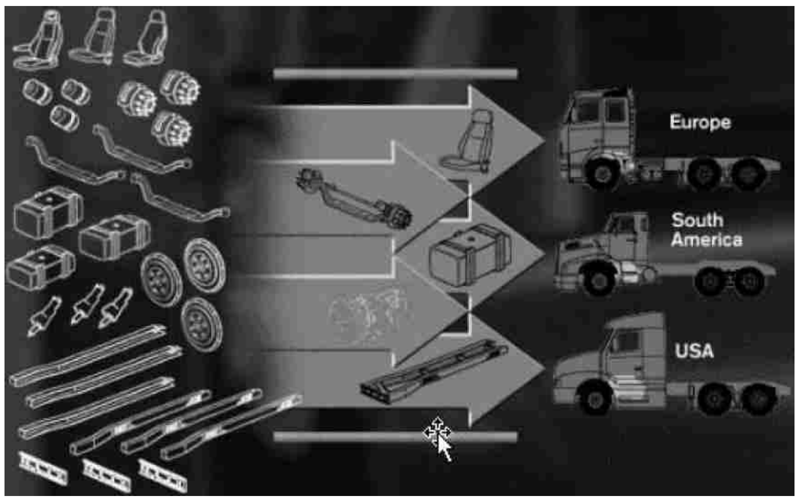

Figure 2.15: Volvo Family Platform-Base Design (Courtesy of Volvo)

An integrated approach model to integrate product design and assembly process development to reduce design and lead-time has been presented by (De Lit, 2003) to improve quality and cost. The proposed CISAL project deals with product family and assembly line design without treating the step between the functional specifications and the product design. An approach by Eguia (2013) was proposed to design and sequence product family in a reconfigurable disassembly manufacturing system. Previous researches designed and proposed design methodologies to design product families to be accommodated in manufacturing systems. The markets demand for needed functions and performance of the products was neglected, as customers' expectations have no influence on the product design. All previous models considered product families on components, module level, and/or part level to generate a product. However, the product families on enterprise level was not discussed in details to understand the level or product variations in relationship to market shares and market segments

2.10 Business Planning and Strategy

Business strategy and product planning are extremely crucial and important concerns to all organizations to make strategically decisions that focus on achieving competitive advantage. The former CEO of AlliedSignal and Honeywell stated: "Strategies most often fail because they aren't executed well. Things that are supposed to happen don't happen" (Bossidy, 2002). The global competition forced companies change their internal and external business philosophies and strategies accordingly. The philosophy of monopoly business and market domination does not exist anymore. Continuous research and development became necessary and part of company budget expense. New and unique products should be presented to customers periodically. In the early 90s, new car models and design used to be introduced to the market every 8-10 years. Recently, most OEMs reduced the program life cycles between 3-5 years. Other industries reduce the life cycles to six months, as in computers and softwares. Nevertheless, every car model should be equipped with new technology to attract and divert attentions of new buyers. Most likely new technology might not be visible to customer, and the best method to market new features is to offer test-drive trials. In early 2009, Ford Motor Company launched a marketing campaign called "Drive-Ford" and offered a free gift with every test drive.

In any industry, including the automobile industry, new features and technologies must be update on regular bases. Products should differentiate themselves from others by increase market shares. Great differentiations attract new customers and increase revenue. The differentiation and diversification in the automotive industry comes includes vehicle size and platform and vehicle family class, which essentially serve a certain market segment. Product variation may stimulate sales volume and generate revenue. However, the increased portfolio in product variations increases costs associated to an exponential growth of complexity, increases efficiency risk factors in manufacturing processes, and deters the benefits of economy of scale. Pine (1993) conducted a research and reported that companies give customer more choices than they actually need. A study conducted by Toyota indicated that only 20% of vehicle variety accounted for 80% of its sales.

From business perspectives, extensive researches and studies were conducted recently and several models, frameworks, and business planning were proposed to measure diversification index, market uncertainty, customer behavior, market competition, and leadership. The two frameworks of business strategy are the Miles and Snow strategy by Shortell (1978), and Porter typologies. Porter (1990), after several years of researches on business planning and corporate strategies in the global competitive market, proposed a business planning framework model which suggests that an enterprise should adopt at least one strategy to survive in the global competitive market. The identified strategies are: 1) Leadership, 2) Innovation, 3) Technology, and 4) Cost. The four strategies were highly accepted business planning and strategies for obvious reasons. Profit, revenue, customer satisfactions are the core scopes of any business, which can be achieved by reducing cost, new technology development, innovation, and strong leadership.

Several researches adopted Porter's proposed strategies and presented different methods and frameworks for achievement. A relationship between appearance and design was proposed by Breeman (1999) and the benefits of appearance. Design appearance reflects customer personality and enterprise brand image. Sophisticated and elegant designs in the automotive industry represent prestige and high-class level. Enterprise DAN with respect to new design and aesthetic should be always kept in mind to keep the identity of the brand (Smyth, 2000).

Heuristics method was presented by Kohli (1990) to design a product-line using conjoin analysis to target individual customer and certain market segment. To optimize the most profitable product, Michalek (2011) develop a novel and unified method for designing lines of products for markets with heterogeneous preferences when technical complexity restricts the attainable space of product attributes. The proposed model used physical model and conjoint-based consumer choice data based on the configuration theory. In addition, Michalek demonstrated that high-performing businesses of one strategy type have a different cultural orientation than high-performing businesses of the other strategy types

It is very essential for any enterprise that the organizations architectures much match its business philosophy and strategy (Drazin and Van de Ven, 1985; Miller and Mintzberg, 1988). According to Doty (1993) theory which states that each business strategy there is a configuration of organizational characteristics that best complements the strategy to yield superior performance. Slater and Olson (2001) studied the relationships between corporate performance and marketing strategy, while Olson (2005) and Vorhies (2003) studied the relationships between corporate performance and the structure of the marketing organization. More researches conducted by Slater (2010) to develop a theory to find the relationship between the marketing organization culture and performance to the business strategy.

Top performing businesses rate portfolio management higher than poorer performers, which is a crucial senior management challenge. Product portfolio and management strategy for new products has been investigated by Robert (2001) and identify four goals and benefits: maximizing the value of the portfolio, ensure that portfolio is strategically aligned, balance between projects and resources, and seek the right balance of projects. A heuristic genetic algorithm model was proposed by Jiao (2007) to plan product portfolio. The algorithm model introduced a generic encoding scheme to synchronize product portfolio generation and selection coherently.

All found that different business strategy types did not discuss and evaluate product portfolio on function and functions attributes level, with respect to market shares.

2.11 Research Gap

Product variations optimization is extremely a complex process. Few researchers (Mistree *et al*., 1993; Simpson *et al*., 1996) applied programming and analysis techniques to design an optimization mode toward product families. The optimization considered strictly current product evaluation with ignorance to market shares, features, functions enterprise position in the competitive market, marketable features, cost of products, and market segments.

In the automotive industry, scholars and researchers focus on methods of design product platform and product families. Some metrics were developed by Ishii *et al* (1995), and Martin and Ishii (1997) to evaluate the importance and cost of product variety. The work emphasized on one-to-one correspondence between functionality and components and assumed component combination creates product variation. The metrics is correct but only applies for simple products where functional differentiation is directly embodies by specific components.

Shijia *et al* (2009) introduced an approach to solve product family appearances customization based on family style and design DNA. Relationship between DAN and product design was analyzed with the introduction of framework model. The research focused on future concepts with respect to design DNA and customized products. The product design DNA was established based on the product style, where in mass production industry, products are designed around the design DNA boundaries. Shijia framework input elements for platform requirement was limited to design aspects such as color, shape, and style, with the deficiency of evaluating customer needs to functions, function attributes, market demand and market shares. Customized products are limited to a certain segment of users and considered to be non-platform product in the product platform classification. ElMaraghy (2009) illustrated in Figure 2.14 the classification of the automotive variation in a hierarchy method.

Product variations are important to meet customer needs and face the global competition. Several researchers proposed different methods and models to manage product variations more effectively. A board range or optimization models were presented to reduce manufacturing cost, improve supply chain management, and be more responsive to market fluctuation. Up to our knowledge, all researches attempted to work around existing product variations and handle them more efficiently, but very few attempted to analyze what variation is mostly needed to meet customer demand without losing the market share. Reducing product variations by identifying the most profitable features, parts, and functions, with the highest demand will relief the industry from managing unnecessary variations. Working around existing issues does not solve the root-cause of the issue.

In summary, establishing product families and platform is an extremely important area of research on different levels, design, manufacturing, reputation, and market share stability, customer perception toward new model design, and product evolution over time. This research will introduce a mathematical model approach for an enterprise to assess and evaluate production variations with respect to the global competitive industry and market shares.

	Dissertation	Eun Suh	AlGeddawy (20xx)	ElMaraghy (20xx)	Seung (2008)	Roy (2011)	Martin & Ishii	Li & Azarm	Conzalez Zugasti et.al	Petrin (2003)	Xzie (2003) Renbin (2008)	Kuang (2008)	Olivier & Suh (2006)	Simpson PPCEM (2001)
Design proposal		X			X			X	X					
Market uncertainty analysis		X			X		X	X	X				X	
Design uncertainty		X			X			X	X					
Critical platform element		X												
Create Flexible design		X	X				X							
Determine design cost,		X												
Functions										X				
Product variation management			X	X										
Synthesis of new product and mfg. system			X											
Pricing (supply chain, Image)						X				X				
Design & mfg .complexity			X	X										
Econometric concerns										X				
Axiomatic Design – product quality											X			
relationship between product image & DP				X								X		
Reactive Product Platform Design – Cladistics -			X	X										
Market segment grid (marketing, MGT, Eng.	X													X
Product variety & architecture	X			X										
Platform & family : functions diversification & analysis	X													
Functions and function attributes	X													
Product family & platform : saturations assessment	X													
Market shares and segment	X													
Marketable functions	X													
Example	Auto	Auto			Power tool	Auto	Water cooler	screw driver	Space- craft			Mobile phone	BIW Frame	Electric motor

Table 2.3: Technical Literature Review

3. CHAPTER THREE - PRODUCT PLATFORMS AND FAMILIES MODEL APPROACH

3.1 Introduction

Products can be described in terms of their features and benefits. Features are product characteristics and identify delivered benefits to target users. While features are easy to describe and detect, product benefits are more tangible and requires some effort to explain. The most compelling product benefits are those that can meet customer needs. Product benefits can be identified by considering customer’s viewpoints. Usually survey and customer feedback are the most beneficial methods to understand expectations and potential improvement that can be accommodated in the next design model (As illustrated in Appendix B). Understanding product features and benefits increase market share by describing product in marketing collateral, publication, advertisement, or in personal selling situation. Features distinguish and differentiate product from competitors as it vary from product model to another and from one manufacturer to another. Product features are the magnets to attract current and new customers.

Product features can possibly be defined in many ways which really depends on the overall description of the product, related industry, and level of description. On part level, part features is classified by ElMaraghy (2008) by either geometric (such as flat, cylindrical, and conical) or functional features (such as holes, slots/grooves, gear teeth, key ways, chamfers and threads.

In the automotive industry, features can be classified into mechanical, electrical, convenience, seats and trims, design and body, safety and security, powertrain, off-road capability, lighting and visibility, instrumentation, entertainment, capacity, aerodynamic, quality, and …etc. Products are represented as sets of product features which customers appreciate and value the freedom of selecting different values relative to the base line. Features are unique characteristics which have influence consumer purchasing patterns. Each of these features serves and offer single or multiple functions. Features and functions are usually work hand-in-hand and are coupled together to create a final product. Functions, across and between products, are classified to be either unique or exclusive. Functions and functions attributes have a significant contribution to classify an enterprise be an industry leader, industry following.

Some features are common across the industry but the functions and the functions attributes what are differentiate them from others. For example, today, the entertainment features in automobile is a standard feature. However, CD players, MP3 connector, and sound quality improve the perception toward features. Function attributes like six CD changer, number of speakers, and number of MP3 adopters, make a difference in attracting customers.

Other features contain exclusive and marketable functions, which are considered to be a marketable key factor to promoting new vehicles. A hybrid engine is a very unique function to promote a product. The function attribute of the engine is the fuel consumption per mile (MPG).

3.2 Current Product Platform Models Evaluation and Modeling

The proposed optimization and evaluation process are utilized to evaluate current product models under one certain platform which serves a certain market segment. The process precedes the actual product platform models where each individual model is investigated and evaluated. The evaluation will include and compare functions and function attributes within the same platform, and against other platforms within the same family. Further optimization will accommodate and adopt platform analysis within the product family and other competitors. Final analysis will be conducted between product families within an enterprise. The product family optimization will eventually be benchmarked with other manufacturers on various levels including, market share domination, financial share value which essentially reflects enterprise review and profit.

The following steps draft a close review of the optimization process and sequence, on different levels as illustrate in figure 3.1.

1- Identify and select a certain product family
2- Identify and select a certain product platform
3- Identify product models offered by the platform.
4- Evaluate differentiation gaps between models.
5- Compare platform to market and competitors
6- Optimize product model selection
7- Final decisions and recommendations
8- Utilize proposed mathematical model to design future products

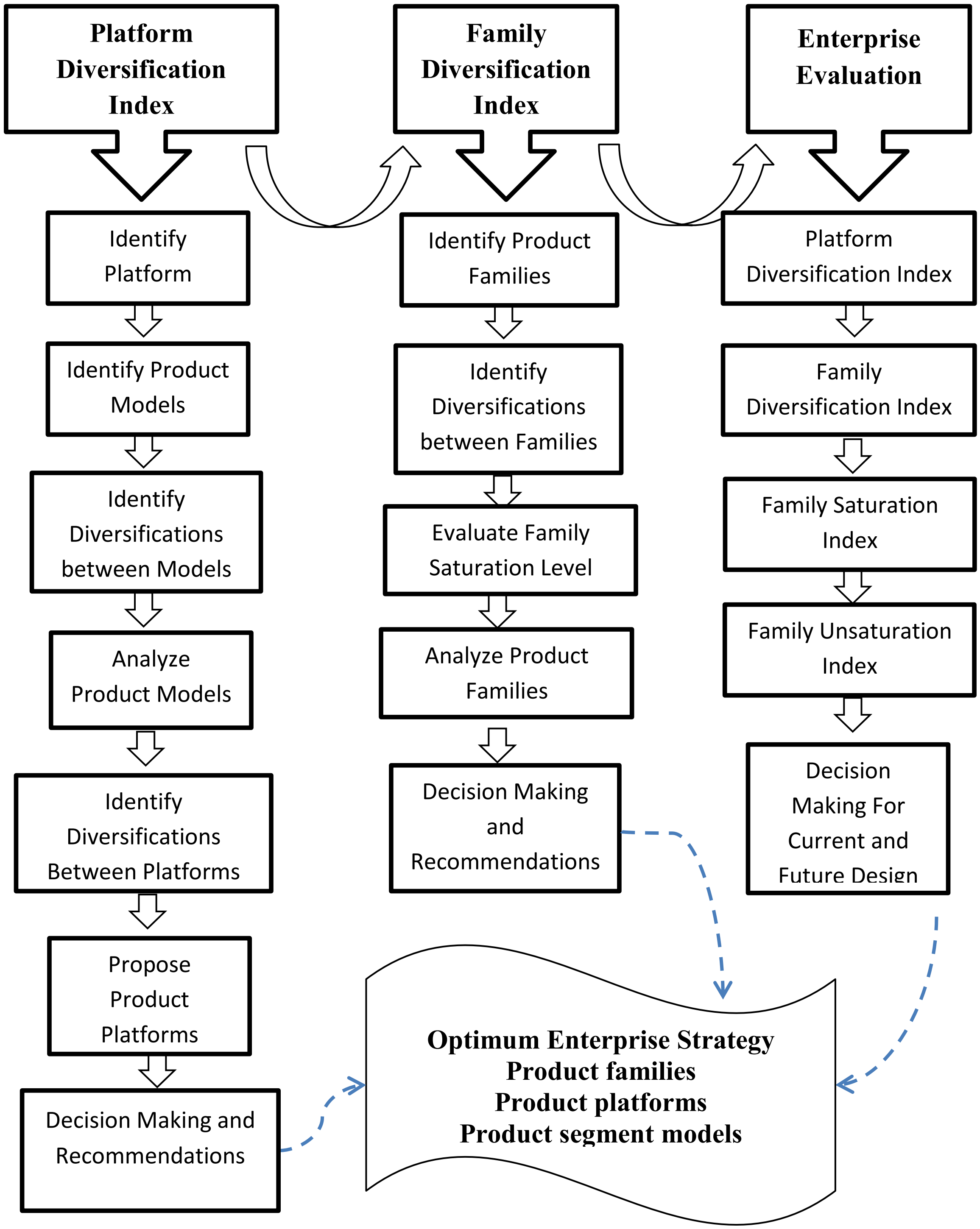

Figure 3.1: Enterprise Design Process

3.3 Platform Diversification Index (PDI)

Scientifically, any product family contains several platforms; every platform satisfies a particular customer needs and expectations. For example, pick-up truck with four wheel drive and flat-bed are generally used in the construction industry, where compact-size vehicles are mostly used by student, single individual, or long drive commuter for gas consumptions. Customer needs are described by targeted market segment, and features which contain functions, and function attributes.

Choosing a random vehicle from the automotive industry, an engine is considered to be a function which delivers a specific need to the market. Function attributes of the engine function are horsepower, number of cylinder, and gas consumption.

Potentially, each and every platform offer functions which can be quantified as:

1- Standard function: standard functions are usually offered by all platforms. Seating, Engine, doors …etc.
2- Exclusive function: which offered by either platform model which differentiate the platform model among others, as a result of long research and development process over time. New market segment, towing capability …etc.

Furthermore, standard functions are classified, within the same platform and across platforms, into two categories in response to the functions attributes of each function:

1- Common functions: Are function which share same function attributes in values. Two engines with same horsepower and gas consumptions
2- Marketable functions: are functions share same function attributes but different in values. Two engines, each engine has different horsepower, number cylinders, and gas consumption per mile, which ultimately leads to Hybrid or electrical powered engine versus combustion engine.

The platform diversification index evaluates the diversification degree between platforms with a score results. Zero indicates no diversifications, and platforms become more unique and diversified as the number grows and moves away from the zero.

Nevertheless, when two platforms are widely different, it is not necessary that each or both platforms need the market needs. Further evaluation of each platform to analyzed with details. The analysis will investigate the saturation point of offered function, features, function attributes, and benchmarking with competitors.

3.4 Family Diversification Index (FDI)

Product family contains several product platforms with wide variety or platform models. The Family Diversification Index (FDI) is an extension analysis of the product platform. Both analyses will establish a healthy wealthy enterprise with profitable margin and higher market share. Profitable margin is generated by avoiding redundancy of the product platform in another product family. For instance, General Motors at some point of its era had several product families, Pontiac, GMC, Chevrolet, Cadillac, Hummer, Opel, Saturn, and others. Majority of the product platforms are identical across the product families. All cost associated to the product development are almost double, despite using the modularity strategy. Automotive manufacturers still need to certify vehicles to meet the National Highway Transportation Safety Association (NHTSA) requirement and safety regulation. A rough estimate, each certification crash has a potential cost in the range of half a million dollars. In addition, validation cost and other associated design integrity validation to ensure comparability and coupling between modules. On top of all engineering cost, manufacturing cost is another factor. Manufacturing and assembly plants have certain capacity to make a certain amount of vehicles per hour. When production capacity is reached due to a long cycle time and inflexibility in manufacturing system, a plant expansion or even a new plant is required to accommodate the new platform build.

As a result, enterprise should carefully study the market needs and market segments. Producing products of the same platform across two different product families is totally unhealthy, and lead to self-competition with unfavorable results.

The main scope of this research is to analyze current product families of an enterprise, and compare to other manufacturers. The outcomes of the analysis will identify the appropriate amount of product family that any enterprise should hold and consecrate on the core product families. Core product families usually are the blood of the organization, which include its DNA and differentiate itself in the market.

A quick comparison example of GM van-vehicle platform between three families, Oldsmobile, Chevrolet, and Pontiac, a clear observation can be noted that all three models are almost identical. The only major noticeable difference is the front grill to represent the family DNA.

	Oldsmobile Silhouette	Chevrolet Venture	Pontiac Montana
Front View			
Rear View			
Interior view			
Annual volume	23,391	130,028	83463

Table 3.1: Van-Platform Comparison

To translate product platform diversification between families into customer needs and market segment, table 3.1 illustrates overview representations of similarities and differences between product families, including the entire product platforms.

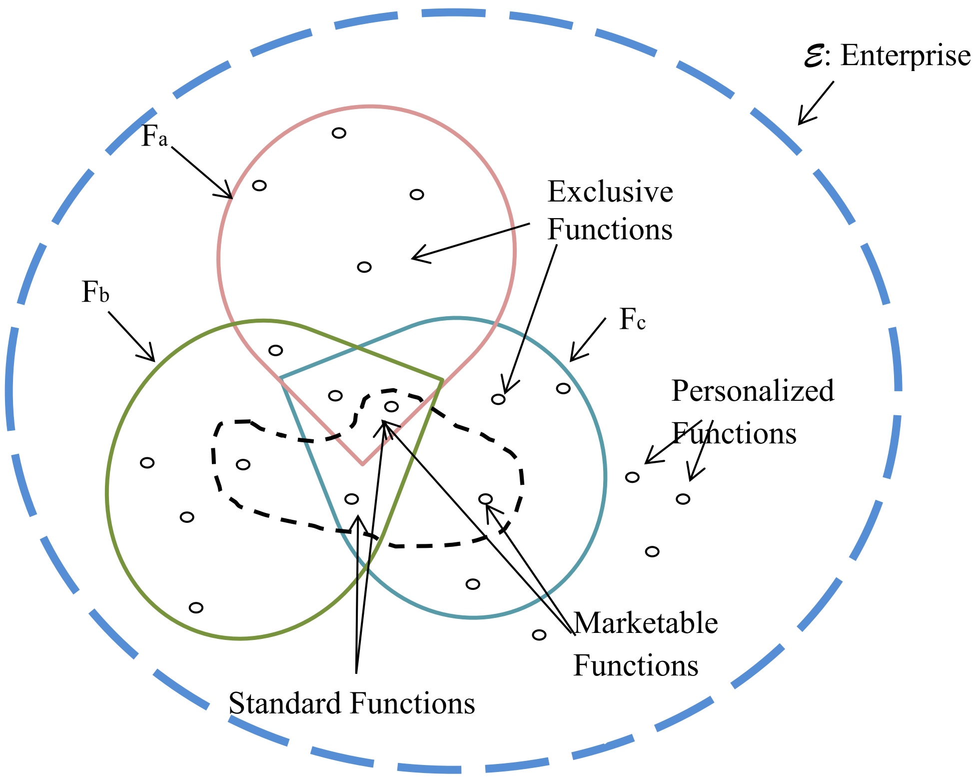

Figure 3.2: Product Families' Function Classifications

Products families, F_a, F_b, and F_c are three different product families offered by the enterprise. Each dot represents certain function and market segment. Each function might be offered by several families. Therefore, further analysis will be conducted to identify the number of each function offered by the enterprise. We will assign a number to each function of repeatability, (X, Y, and Z). X represents the number of repeated functions within the same family. Y, represent the number of repeated functions across the families, Z, represents the number of repeated functions within the enterprise. Qualitative functions such as color, design shape, aerodynamic, are classified to be subjective to customer perception and modern designs. Therefore, qualitative aspects are not encountered, and considered to be beyond the scope of the research.

Typically, automotive manufacturers supply two distinguished product families to serve two different types:

1) Low-end daily use vehicles: targets low to mid class income.

2) High-end luxury vehicles, targets high class income. Each family contains its platforms.

Product families contain many product platforms to serve different market segments depending on the purpose of the use, whether for construction, transportation, low income, daily use, family use, luxury, and ..etc. The more product platforms the more targeted segments are served. Compiling all products platforms in the market, we observe the following segments classification:

Product Platforms in Market					
subcompact-size vehicle	SUV compact	crossover compact	pick-up compact	Minivan	sport
compact-size vehicle	SUV mid-size	crossover full-size,	pick-up mid-size	van full-size	sport executive
compact-size vehicle executive	SUV full-size		pick-up full-size		road star
mid-size executive					
mid-size vehicle					
full-size vehicle					

Table 3.2: Automotive Enterprise's Market Segment Platforms

In the optimization model, each platform earns one point value in the exclusive functions section, as long as the other product family does not offer the same platform. One additional point is assigned to each platform class.

3.5 Family Saturation Index (FSI)

The evaluation of the diversification level between product families does not necessary mean that product families are equipped with all expected functions to meet customer expectation. The diversification index identifies the degree of diversifications between families. However, further analysis is needed to fully understand if any product family is saturated and contains all product platforms to meet and fulfill customer needs and market segments. Standard functions between the product families are considered perfect saturation and assigned (+) for the index. Common functions earn one point and then normalized by the number of repeatability between families (Chen,1976). SFI assesses the values of marketable functions attributes. The assessment evaluates functions attributes of a family which are covered by others.

3.6 Family Unsaturation Index (FUI)

The Unsaturation Family Index (UFI) is an index to evaluate functions that exist in (F_{N-a}) family and not available in the evaluated family (F_a). UFI scores and evaluates function attributes values by assigning values, 0 or 1. A family with score of (0) means it is saturated and contains all functions offered by other families. In contrast, a family with (1) means the family is not saturated and not all functions offered by other families are included in the evaluated family (F_a).

3.7 Model Approach

The first step of the process is to identify target enterprise $\mathcal{E}$ to be evaluated. An enterprise is consist of N families of platforms, $\mathcal{E} = (F_1, F_2, F_3, \dots F_N)$. Each and every family F_i contains several P_N platforms: $F_i = (P_{i,1}, P_{i,2}, P_{i,3}, \dots P_{i,N})$. It is assumed each product platform is set of product models to serve a market segment and end-users needs. For example, flatbed trucks are designed to serve construction industries, car-van vehicles platforms are designed to serve family oriented market segment. Midsize vehicle platforms to large size vehicle platforms are designed for market segment user who prefer driving low point of gravity vehicles, for daily and average commute and serve day-to-day activates. Understanding market segment needs in relationship to product preference is behind the scope of this dissertation.

Each platform $P_{i,N}$ in a family is consisting of M_n models. $P_{i,1} = (M_{i,1,1,}, M_{i,1,2}, M_{i,1,3}, \dots M_{i,1,n})$. As explained previously, platforms are designed to serve and offer single or multi functions to meet certain market segment and customer needs. Any given function can be available in multi platforms within the enterprise. For instance, entertainment function can be offered across the product platforms and product

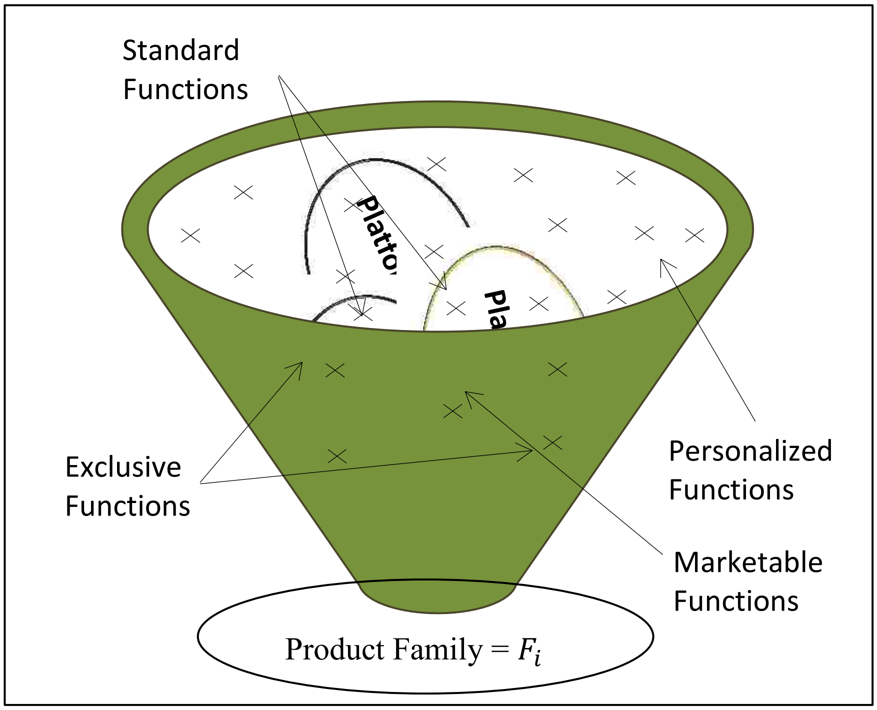

Figure 3.3: Set Of Functions

families. However, towing capability is only offered in certain platforms. Let $\mathcal{F}$ to represents all functions offered by all models and platforms within a product family: $\mathcal{F} = (f_1, f_2, f_3, \dots . f_F)$. Figure 3.4 below illustrates all functions offered by all models across the entire product family.

Let $m_{i,r}^t$ be assigned to each function f_t in $\mathcal{F}$ when it is available in the platform $P_{i,r}$ .by agreement, $m_{i,r}^t$ = ZERO when function f_t is not offered by platform $P_{i,r}$. Assuming, each function can be presented as a set of attributes. For instance, vehicle interior volume can be presented by several function attributes: number of passengers, legs room, distance between driver and passenger seats, headliner height, manual verses automatic...etc. Each function f_t in $\mathcal{F}$, has T_t function attributes, donated, therefore:

$T_t = (b_1^t, b_2^t, b_3^t, \dots b_{T_t}^t)$. In addition, every function f_t might be repeated more than once within the same product platform, therefore, every function attribute has different value. For example, the seating function with number of passengers as function attributes; the value of the function attributes ranges between two passengers up to seven passengers. Therefore, we donate $U_l^t(i, r)$ as a value of function attribute b_l^t for the function f_t in product platform $P_{i,r}$, in product family F_i

3.8 Platform Diversification Index (PDI)

Platform and/or car-model analysis identifies the functions spread of a given platform within the same family F_i. Per agreement, f_t is a function in $\mathcal{F}$ (set of all functions). Let b_l^t be the function attribute in family F_i and function f_t, $F_i(f_t)$. Each attributes hold a value, and the maximum difference between the two values for the same attribute are donated by Δb_l^t , and defined by:

$$\Delta\, b_l^t = MAX_{P_{i,r} \in F_i}\{U_l^t(i,t)\} - MIN_{P_{i,r} \in F_i}\{U_l^t(i,t)\} \qquad (3.1)$$

Within the same family F_i, three given platforms, $P_{i,a}$ and $P_{i,b}$, $P_{i,c}$ which all share a function f_t Despite all platforms share same function, each function attribute b_l^t might hold a different value in each platform , $U_l^t(i,a)$, $U_l^t(i,b)$, and $U_l^t(i,c)$ respectively. Attribute Distance Ratio is calculated by comparing the two values to the overall distance.

$$\text{Attribute Distance Ratio } (adr)\ (P_{i,a}, P_{i,b}, b_l^i) = \frac{|U_l^t(i,a) - U_l^t(i,b)|}{\Delta\, b_l^t} \qquad (3.2)$$

$$\text{Attribute Distance Ratio } (adr)\ (P_{i,b}, P_{i,c}, b_l^i) = \frac{|U_l^t(i,b) - U_l^t(i,c)|}{\Delta\, b_l^t}$$

$$\text{Attribute Distance Ratio } (adr)\ (P_{i,a}, P_{i,c}, b_l^i) = \frac{|U_l^t(i,a) - U_l^t(i,c)|}{\Delta\, b_l^t}$$

Taking the sum of all *adr* for each function, over the number of function attributes T_t in the function, we find the Function Distance Ration (*fdr*) :

$$fdr(P_{i,a}, P_{i,b}, f_t) = \frac{1}{T_t} \sum_{l=1}^{T_t} \frac{|U_1^t(i,a) - U_1^t(i,b)|}{\Delta\ b_1^t} \tag{3.3}$$

$$fdr(P_{i,b}, P_{i,c}, f_t) = \frac{1}{T_t} \sum_{l=1}^{T_t} \frac{|U_1^t(i,b) - U_1^t(i,c)|}{\Delta\ b_1^t}$$

Per equation, the *fdr* = Zero only if all functions attributes of $f_t$carry the save values in all platforms, by agreement$1 \geq fdr \geq 0$.

3.8.1 Standard Platform Differentiation Function Analysis (PDFAs)

To analyze the Platform Differentiation Score for standard functions (PDSs), we assign:

$\mathcal{F}_{(i,\, a+b)}$: Sum of all functions available in both $P_{i,a}$ and $P_{i,b}$

$\mathcal{F}_{(i,\, b+c)}$: Sum of all functions available in both $P_{i,b}$ and $P_{i,c}$

PDFAs considers both common and marketable functions, which can be calculated by adding all fdr of all repeatable functions between two platforms individually:

$$PDFAs_1(P_{i,a}, P_{i,b}) = \sum_{\substack{f_t available\ in \\ (P_{i,a}, P_{i,b})}} fdr\big(f_t, P_{i,a}, P_{i,b}\big) \tag{3.4}$$

$$PDFAs_2(P_{i,b}, P_{i,c}) = \sum_{\substack{f_t available\ in \\ (P_{i,b}, P_{i,c})}} fdr\big(f_t, P_{i,b}, P_{i,c}\big)$$

3.8.2 Exclusive Platform Differentiation Functions Analysis (PDFAe)

Product platforms not necessary have the same functions, as indicated previously, in considering for exclusive functions in the PDI for the given $P_{i,b}$ and $P_{i,a}$, $P_{i,c}$, we assign:

$\mathcal{F}_{(i,\, a|b)}$: Sum of exclusive functions available in $P_{i,a}$ or $P_{i,b}$

$\mathcal{F}_{(i,\, b|c)}$: Sum of exclusive functions available in $P_{i,b}$ or $P_{i,c}$

Therefore, the exclusive functions analysis can be found by:

$$PDFAe_1(P_{i,a}, P_{i,b}) = \mathcal{F}_{(i,\, a|b)} \tag{3.5}$$
$$PDFAe_2(P_{i,b}, P_{i,c}) = \mathcal{F}_{(i,\, b|c)}$$

By considering all platform different functions, common and exclusive, we now can calculate the platform diversification index (PDI) by:

$$PDI(P_{i,a}, P_{i,b}) = \frac{PDFAs_1(P_{i,a}, P_{i,b}) + PDFAe_1(P_{i,a}, P_{i,b})}{\mathcal{F}_{(i,\, a|b)} + \mathcal{F}_{(i,\, a+b)}} \tag{3.6}$$

$$PDI(P_{i,b}, P_{i,c}) = \frac{PDFAs_2(P_{i,b}, P_{i,c}) + PDFAe_2(P_{i,b}, P_{i,c})}{\mathcal{F}_{(i,\, b|c)} + \mathcal{F}_{(i,\, b+c)}}$$

Per equation, PDI satisfies the condition $0 \leq PDI(P_{i,a}, P_{i,b}) \leq 1$, in which that:

$PDI(P_{i,a}, P_{i,b}) = 0$: When both platforms share the same functions and function attribute values.

$PDI(P_{i,a}, P_{i,b}) = 1$: When no functions are shared, or all attribute values are totally different on all functions:

$PDI(P_{i,a}, P_{i,b})$ calculates the initial diversification between any two platforms. The second step is to understand the diversification of any platform in relationship to the rest of the platforms within or between product families. Given$PDI(P_{i,b})$, we calculate the average of all $PDI(P_{i,b})$ for every $(P_{i,b})$ in the family

$$PDI_{F_i}(P_{i,b}) = \frac{1}{(F_N - 1)} \sum_{P_{i,c,a} \in F_{i,}\ b \neq a, \neq c} PDI(P_{i,b}, P_{i,a}), PDI(P_{i,b}, P_{i,c}) \qquad (3.7)$$

$$PDI_{F_i}(P_{i,a}) = \frac{1}{(F_N - 1)} \sum_{P_{i,c,b} \in F_{i,}\ b \neq a, \neq c} PDI(P_{i,a}, P_{i,b}), PDI(P_{i,a}, P_{i,c})$$

$$PDI_{F_i}(P_{i,c}) = \frac{1}{(F_N - 1)} \sum_{P_{i,a,b} \in F_{i,}\ b \neq a, \neq c} PDI(P_{i,c}, P_{i,a}), PDI(P_{i,c}, P_{i,b})$$

Where F_N is the number of product platforms involved in platform diversification index.

The Platform Efficiency Power EP_p in the market shares of any given platform in relationship to other platforms can be achieved by:

$$EP_{p_{(P_{i,b})}} = \left(PDI_{F_{i\,(P_{i,b})}} * (\%\, M_{s_{(P_{i,b})}}\right) \qquad (3.8)$$

Where M_s is the Market Share value per platform between evaluated platforms.

$$M_{s_{(P_{i,b})}} = \left(\frac{\text{Sold Vehicles } (P_{i,b})}{Total\ Sold\ Vehicles}\right) * 100 \qquad (3.9)$$

$$M_{s_{(P_{i,a})}} = \left(\frac{\text{Sold Vehicles } (P_{i,a})}{Total\ Sold\ Vehicles}\right) * 100$$

Therefore, the Dominated product Platform (D_p) for an enterprise to maintain with respect to profit and market share can be achieved by:

$$D_{p(F_i)} = \left(\frac{P_i}{\text{Max } PE_p}\right) * 100 \qquad (3.10)$$

3.9 Families Diversification Index (FDI)

Analyzing the diversification of product platform, within the same family or between several families, lead the analysis to the second level, which is the Family Diversification Index (FDI), FDI is simply an extension of the platform analysis. The index investigates the differences between product families within the enterprise. Product families are then analyzed to understand what families are the most profitable to adhere to, and families should be discontinued from the market. The analysis takes the enterprise to the send level to benchmark itself among other competitors and add additional features and function in deficient areas. As illustrated in figure 3.3, an enterprise may consist of two or more product families. Each family offers several and different functions. Each function is identified as either standard or exclusive. Of course, some functions are unclassified to server personalized and customized options. Let F_a and F_b be two families with functions. Three numbers are assigned to each and every function. Each digit represents the number of repeatability of its function within the enterprise. For example in product family F_a for the entertainment function, (2, 4, 5) indicates that this function is repeated twice in F_a, four times in F_b, and five times in the enterprise. Potentially, the number of digits grows proportionally as the number of product families grow. For instance, an enterprise with 5 product families, the values will be as (2, 4, 6, 2, 0)

3.9.1 Exclusive Family Differentiation Functions Analysis (FDFAe)

Considering all exclusive functions between product families, a family is selected and compared against other families to identify the exclusive functions among others.

Family exclusive efficiency is identified as:

$\mathcal{F}\,(F_a - F_{(b+c)})$: set of functions available in F_a only, and supersedes F_b and F_c functions, which is considered as an efficiency for F_a

$\mathcal{F}\ (F_b - F_{(a+c)})$: set of functions available in F_b only, and supersedes F_a and F_c functions, which is considered as an efficiency for F_b

Family exclusive deficiency is identified as:

$\mathcal{F}\ (F_{(b+c)} - F_a)$: set of functions available in F_b and F_c only, and supersedes F_a functions, which is considered as an deficiency for F_a

$\mathcal{F}\ (F_{(a+c)} - F_b)$: set of functions available in F_a and F_c only, and supersedes F_b functions, which is considered as an deficiency for F_b

For each function F_t in every product family, we calculate family efficiency and deficiency scores for each product family:

Exclusive Family Efficiency Score (FESe) (F_a, F_b)=

$$\sum_{f_t \in F_{(a-b)}} \frac{R_t^{a-b}}{L_t} \qquad (3.8)$$

Exclusive Family Deficiency Score (FDSe) (F_a, F_b)=

$$-\sum_{f_t \in F_{(b-a)}} \frac{R_t^{b-a}}{L_t} \qquad (3.9)$$

Where:

R_t^{a-b}: Number of function repeatability in the product family (F_a) over (F_b)

R_t^{b-a}: Number of function repeatability in the product family (F_b) over (F_a)

L_t = Total number of repeatability of the function in the enterprise

3.9.2 Standard Family Differentiation Functions Analysis (FDFAs)

The standard functions between product families need to be analyzed by looking at the function attributes and associated values. Let F_t be a function in $\mathcal{F}F_{(a+b+c)}$, which is a shared function between F_a , F_b and F_c. Let b_l^t be a function attribute for F_t. Let $\boldsymbol{U}_l^{\mathrm{t}}$= $(\boldsymbol{u}_{l,1}^{\mathrm{t}}, \boldsymbol{u}_{l,2}^{\mathrm{t}}, .. \boldsymbol{u}_{\mathrm{l,T}}^{\mathrm{t}})$ to represent the all possible different values for each function attribute b_l^t in every function F_t. In addition, we donate $\theta_{l,i}^t, \vartheta_{l,i}^t$, and $\delta_{l,i}^t$, as the number of repeatability of each value in F_a , F_b and F_c (respectively) in every function.

Considering all standard and marketable functions available between product families, we assign the following:

$\mathcal{F}F_{(a+b+c)}$: set of functions available in F_a and F_b and F_c

Therefore, for example, the attribute efficiency and deficiency scores for F_a can be calculated as following:

Attribute Efficiency Score (AESs) = (3.10)

$$f = \begin{cases} \theta_{l,i}^t > \vartheta_{l,i}^t,\ \theta_{l,i}^t > \delta_{l,i}^t, & \textit{function is available} \\ 0, & \textit{othersie} \end{cases}$$

$$(f_t, b_l^t, F_a, \rightarrow F_b, F_a, \rightarrow F_c) = \sum_{\substack{i=1 \\ \theta_{l,i}^t > \vartheta_{l,i}^t}}^{T} \frac{(\theta_{l,i}^t - \vartheta_{l,i}^t) u_{l,i}^t}{u_{\mathrm{l,T}}^{\mathrm{t}} - u_{l,1}^{\mathrm{t}}} + \sum_{\substack{i=1 \\ \theta_{l,i}^t > \delta_{l,i}^t}}^{T} \frac{(\theta_{l,i}^t - \delta_{l,i}^k) u_{l,i}^t}{u_{\mathrm{l,T}}^{\mathrm{t}} - u_{l,1}^{\mathrm{t}}}$$

Attribute Deficiency Score (ADSs) =

$$f = \begin{cases} \theta_{l,i}^t < \vartheta_{l,i}^t,\ \theta_{l,i}^t < \delta_{l,i}^t, & \textit{function is available} \\ 0, & \textit{othersie} \end{cases}$$

$$(f_t, b_l^t, F_a, \rightarrow F_b, F_a, \rightarrow F_c) = -\left[\sum_{\substack{i=1 \\ \theta_{l,i}^t < \vartheta_{l,i}^t}}^{T} \frac{(\theta_{l,i}^t - \vartheta_{l,i}^t) u_{l,i}^t}{u_{\mathrm{l,T}}^{\mathrm{t}} - u_{l,1}^{\mathrm{t}}} + \sum_{\substack{i=1 \\ \theta_{l,i}^t < \delta_{l,i}^t}}^{T} \frac{(\theta_{l,i}^t - \delta_{l,i}^k) u_{l,i}^t}{u_{\mathrm{l,T}}^{\mathrm{t}} - u_{l,1}^{\mathrm{t}}} \right] \quad (3.11)$$

With $u_{\mathrm{l,T}}^{\mathrm{t}} - u_{l,1}^{\mathrm{t}}$ is defined to be the maximum delta of possible values for each attribute.

By adding all attribute scores for each function and divide by the number of function attributes, the function score is obtained.

Adding all function efficiency score over the total number of shared standard functions, and the Family Efficiency Scored for standard functions (FESs) is achieved by:

Family Efficiency Score for Standard Functions (FESs) =

$$\frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_a, \rightarrow F_c) \right] \tag{3.12}$$

Where T_t represents the total number of function attributes in each function.

Family Deficiency Scores for Standard Functions (FDSs) =

$$-\frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_a, \rightarrow F_c) \right] \tag{3.13}$$

By agreement at, the Family Deficiency Score should be in the negative sign.

By considering the efficiencies and deficiencies for all functions, exclusive and standard, we can calculate the Family Diversification Index (FDI).

The Family Diversification Index is the sum of all previous equation for standard and exclusive functions

Exclusive Family Efficiency Score (FESe) + Exclusive Family Deficiency Score (FDSe) + Standard Family Efficiency Score (FESs) + Standard Family Deficiency Score (FDSs) + # of product platform

FDI = (3.14)

$$\left\{\sum_{f_t \in F_{(a-b)}} \frac{R_t^{a-b}}{L_t} - \sum_{f_t \in F_{(b-a)}} \frac{R_t^{b-a}}{L_t} + \frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t}\sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_c)\right] - \frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t}\sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_c)\right] + \#\ of\ product\ platforms\right\}$$

The Family Efficiency Power EP_f in the market shares of any given product family in relationship to other product family can be achieved by:

$$EP_{f_{(F_b)}} = \left(FDI_{(F_b)} * (\%\, M_{s_{(F_b)}}\right) \qquad (3.15)$$

Where M_s is the Market Share value per product family between evaluated families

$$M_{s_{(F_b)}} = \left(\frac{\text{Sold Vehicles } (F_b)}{Total\ Sold\ Vehicles}\right) * 100 \qquad (3.16)$$

$$M_{s_{(F_a)}} = \left(\frac{\text{Sold Vehicles } (F_a)}{Total\ Sold\ Vehicles}\right) * 100$$

Therefore, the Dominated Family (D_f) for an enterprise to maintain with respect to profit and market share can be achieved by:

$$D_{f_{(F_i)}} = \left(\frac{F_i}{\text{Max } EP_F}\right) * 100 \qquad (3.17)$$

The do mandated product family is highly recommended family to allocated available resources and future investments

3.10 Family Saturation Index (FSI)

The Family Saturation Index (FSI) evaluates and assesses the available functions and functions attributes in the target family (F_a) but not in other families (F_{N-a}). The Family Saturation Index (FSI) investigates the saturation percentage on how (F_a) is saturated with functions and function attributes available against the sum of the other families (F_{N-a}). The FSI focuses on standard functions only that are available in all families. Let (F_a) be the target family to be analyzed against all other families (F_{N-a}). Functions available in (F_{N-a}) but not in (F_a) are analyzed in the Family Unsaturation Index (FUI) section. Let F_t be a function available in all (F_a) and (F_{N-a}), and b_l^t be a function attribute. Let $\boldsymbol{U}_l^{\mathrm{t}} = (\boldsymbol{u}_{l,1}^{\mathrm{t}}, \boldsymbol{u}_{l,2}^{\mathrm{t}}, .. \boldsymbol{u}_{\mathrm{l,T}}^{\mathrm{t}})$ represent all possible values for each function attribute b_l^t in every function F_t, and T represent number of values in each attribute. We assign $\theta_{l,i}^t$ and $\vartheta_{l,i}^t$ as the number of repeatability of each function in F_a, and (F_{N-a}) (respectively). Each Attribute Saturation Score is calculated as:

Attribute Saturation Score (ASS) =

$$\left(f_t, b_l^t, F_a, (F_{N-a})\right) = \frac{1}{T} \sum_{\vartheta_{l,i}^k > 0} MAX\left(1, \frac{\theta_{l,i}^t}{\vartheta_{l,i}^t}\right) \tag{3.18}$$

When $\vartheta_{l,i}^k = 0$ means that values $\boldsymbol{u}_{l,\mathrm{i}}^{\mathrm{t}}$ is not available in other families (F_{N-a}), is not considered in the saturation index, but is covered in the (UFI).

Adding all attributes saturation scores calculates the Family Saturation index (FSI): $\mathcal{F}F_{(a+b+c)}$

Family Saturation Index (FSI) =

$$\frac{1}{\boldsymbol{F}_{\boldsymbol{F_a}+(\boldsymbol{F_{N-a}})}} \sum_{f_t \in F_a, (F_{N-a})} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \mathrm{ASS}\left(f_t, b_l^t, F_a, (F_{N-a})\right)\right] \tag{3.19}$$

Where T_t is the number of attributes in each function

3.11 Family Unsaturation Index (FUI)

In continuation to the Family Saturation Index, the Family Unsaturated Index (FUI) evaluates and assesses the target of study product family's (F_a) functions and function attributes. The FUI focuses on exclusive and standard functions that are available in certain families, which considered being a deficiency for the family in assessment. FUI identifies how the target family does not provide the functions and functions attributes that are available in the other product families.

3.11.1 Exclusive Functions Unsaturation Score (FUSe)

Let (F_a) be the target family for evaluation and analysis, and let (F_{N-a}) be the rest of other product families to be benchmarked against. As it has been assigned to exclusive functions before, we donate $\mathcal{F}((F_{N-a}) - F_a)$ for functions available in all product families (F_{N-a}) but not in (F_a). For each function F_t in $\mathcal{F}((F_{N-a}) - F_a)$, we donate $R_t^{(N-a)-a}$ as the number of availability of the functions in ((F_{N-a}) but not in F_a. We assign $total_f^{a+(N-a)}$ as the total number of all functions availabilities in both (F_a) and (F_{N-a}).

The exclusive Function Unsaturation Score is calculated by:

Exclusive Function Unsaturation Score (FUSe) $(F_{N-a}), F_a$ =

$$\frac{1}{total_f^{a+(N-a)}} \sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a}) \tag{3.20}$$

3.11.2 Standard Functions Unsaturation Score (FUSs)

In addition to the exclusive functions evaluation, the standard functions and function attributes need to be evaluated to understand the missing functions in the target family. Let F_t be a functions available in (F_a) and (F_{N-a}), where (F_{N-a}) represent the sum of all other product families beside (F_a).

Let b_l^t be a function attribute of F_t. Let $\boldsymbol{U_l^{\mathrm{t}}} = (\boldsymbol{u}_{l,1}^{\mathrm{t}}, \boldsymbol{u}_{l,2}^{\mathrm{t}}, .. \boldsymbol{u}_{\mathrm{l,T}}^{\mathrm{t}})$ be all possible values assigned to b_l^t in all product families in the same function. In addition, we donate $\theta_{l,i}^k, \vartheta_{l,i}^k$ as the number of repeatability of F_t in (F_a) and (F_{N-a}) (respectively)

The Attribute Unsaturation Score for standard functions (AUSs) can be achieved by:

Standard Attribute Unsaturation Score (AUSs) =

$$\left(f_t, b_l^t, F_a, F_{(N-a)}\right) = \frac{\sum_{\substack{i=1 \\ \theta_{l,i}^t=0}}^{T} \left(\vartheta_{l,i}^t\right)}{\sum_{i=1}^{T}(\theta_{l,i}^t - \vartheta_{l,i}^t)} \qquad (3.21)$$

After calculating the Attribute Unsaturation Score for each function, the score of all standard functions can be calculated by:

Standard Functions Unsaturation Score (FUSs) =

$$\frac{1}{\boldsymbol{F_a} + \boldsymbol{F}_{(\boldsymbol{N-a})}} \sum_{f_t \in F_{(N-a)-a}} \frac{1}{T_t} \sum_{t=1}^{T_t} \mathrm{AUSs}\left(f_t, b_l^t, F_a, F_{(N-a)}\right) \qquad (3.22)$$

By calculating the both exclusive and standard functions, now we can calculate the entire product Family Unsaturation Index (FUI) by adding both scores and divide by 2, which distributes and normalizes the overall family unsaturation.

As a result, the Family Unsaturation Index (FUI) =

$$\frac{1}{2}\left[\frac{1}{total_f^{a+(N-a)}}\sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a}) + \frac{1}{\boldsymbol{F_a} + \boldsymbol{F}_{(\boldsymbol{N}-\boldsymbol{a})}} \sum_{f_t \in F_{(a+N-a)}} \frac{1}{T_t}\sum_{t=1}^{T_t} \text{AUSs}\,(f_t, b_l^t, F_a, F_{N-a})\right] \tag{3.23}$$

4. CHAPTER FOUR - FORD CASE STUDY

4.1 Ford Motor Company

Ford Motor Company (known as Ford) is an American multinational automaker with a headquartered located in Dearborn, Michigan, U.S.A. The company was founded by the industry legend Henry Ford, and incorporated on June 16, 1903. The company sells automobiles and commercial vehicles under the Ford, Mercury, and Mazda brands, and luxury vehicles under the Lincoln Land Rover, Volvo, Jaguar, and Aston Martin brands. Ford is listed on one of the biggest Stock Exchange market, the New York Stock Exchange. Ford has manufacturing operations worldwide, including in the United States, Canada, Mexico, China, the United Kingdom, Germany, Turkey, Brazil, Argentina, Australia and South Africa. Ford employs 87,700 employees who work for Ford in the U.S.A. and 213,000 employees worldwide, and around 90 plants and facilities worldwide

Ford under the leadership of Henry Ford introduced methods for large-scale manufacturing of cars and large-scale management of an industrial workforce using elaborately engineered manufacturing sequences typified by moving assembly lines. Ford acquired Jaguar, Volvo and Land Rover in 1989, 1999 and 2000 respectively. Jaguar Land Rover sold to Tata Motors in March 2008, and discontinued the Mercury brand.

According to Bertel Schmitt (2011), Ford ranked the second largest U.S. based automaker, and the fifth largest in the world based on 2010 vehicle sales. According to Fortune 500 list, Ford ranked number eight between American based companies in year 2009 with 118.3 billion in revenues. Figure 4.1 presents the number of manufactured and sold vehicles between 1999 and 2012. (All collected sales volume and market shares used in the research were published by WardsAuto Group, a division of Penton Media Inc., 2014)

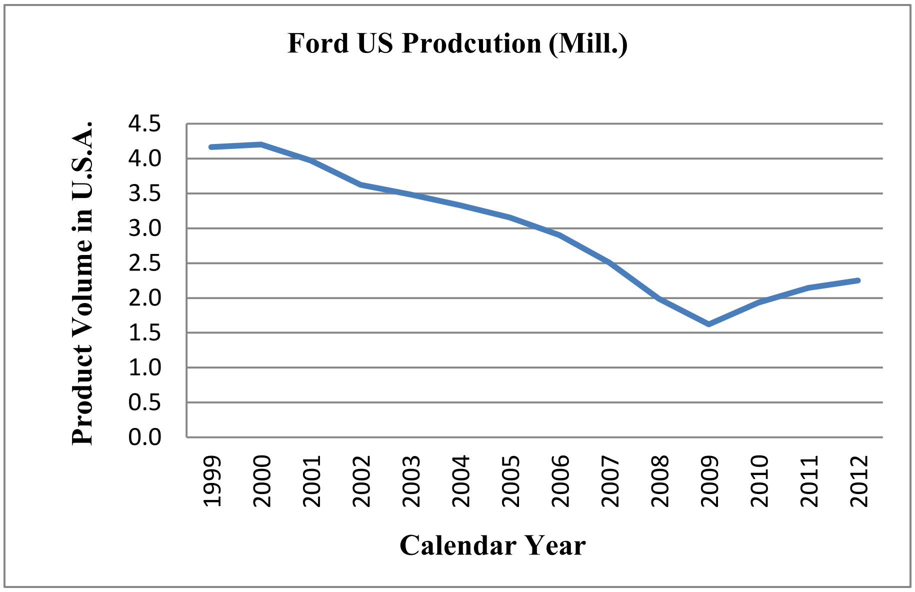

Figure 4.1: Ford Product Volume in U.S.A.

4.2 Case Study Background

In chapter three, the new mathematical model was introduced. Chapter 4 demonstrates the proposed optimization model through an actual case study from the NA automotive industry, where the ultimate product platform and product family must accommodate preferred functions and function attributes desired by end-user in its segment.

A major automotive company was going through a rough and harsh financial situation. The globalization market and financial crises has its negative effects on the organization financially. Low cost vehicles with high profit margin, along with increasing market share are the essential key factor for the enterprise to survive. Solutions are urgently needed to survive in the industry with least negative consequences. Some product families and product platforms need to be discontinued in order to survive the economic crises and maintain market share percentage with respect to marginal profit and cost reduction. The remaining car models need to retain the market segment as well as to attract potential new market segment. The remaining car models, platforms and families, need to replace the discontinued models. All figures and data were collected from the field to optimize and propose an ultimate solution.

4.2.1 Platform Diversification Index (PDI)

Platform Diversification Index (PDI) demonstrates the optimization process by utilizing an actual automotive vehicle platforms manufactured by an OEM and offered to the NA market. The case study selected three different vehicle models from a same mid-size vehicle platform, from two different product families, from the same OEM. Table 4.1 shows an actual production volume each model over the production life of each vehicle

Model Year	Mid-Size Vehicle Platform			Ford Motor Co.
	Ford	Mercury		
	Fusion	Milan	Sable	
2001	55602	0	106,633	
2002	92647	0	55,215	Production Volume
2003	83171	0	44,216	
2004	141108	5321	2,449	
2005	316096	35853	0	
2006	305308	37244	21,121	
2007	321164	31393	16,187	
2008	186694	27403	6,256	
2009	219219	28912	37	
2010	248067	0	0	
2011	241263	0	0	

Table 4.1: Ford Mid-Size Annual Vehicle Production Volume

Production volume of the product platforms of the case study is illustrated in a graphical format as shown in Figure 4.2

The three vehicle models were analysed by identifying all features, functions, and functions attributes. All functions are clustered into two main categories: 1) Standard functions, 2) Exclusive functions. Standard functions are exclusive functions clustering is illustrated in table 4.2. Function attributes and associated values are presented in

Appendix H. qualitative attributers such as front wheel versus rear wheel values earn subjective values based on market demand or engineering feedback.

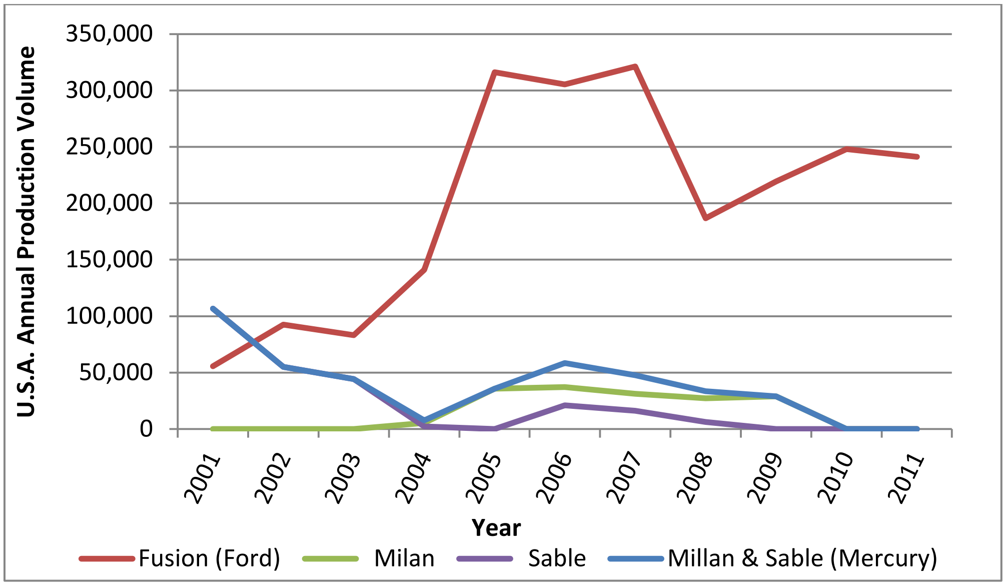

Figure 4.2: Production volume of Fusion, Milan and Sable

Standard Functions		Exclusive Functions
1. Seating 2. Occupancy comfort 3. Entertainment 4. Safety 5. Security 6. Ventilation 7. Exterior dimension 8. Engine 9. Transmission 10. Breaking system 11. Slide braking	12. Drive type 13. Power mechanism 14. Acceleration 15. Handling 16. Fuel economy 17. Rear luggage 18. Tire 19. Access vehicle	1. Towing 2. Sky view - sunroof

Table 4.2: Function Classification

Three given platforms, P_a, P_b, and, P_c which all share a function f_t. Despite all platforms share same function, each function attribute b_l^t might hold a different value in each platform, $U_l^t(i,a)$, $U_l^t(i,b)$, and $U_l^t(i,c)$ respectively.

Considering one function at the time, each attributes hold a value, and the maximum difference between attribute values $\Delta\, b_l^t$ calculates the gap between all platforms, and defined by:

$$\Delta\, b_l^t = MAX_{P_{i,r} \in F_i}\{U_l^t(i,t)\} - MIN_{P_{i,r} \in F_i}\{U_l^t(i,t)\}$$

Function	Function attribute	Ford Fusion Product A (MY 2006)	Mercury Milan Product B (MY2006)	Mercury Sable Product C (MY2006)	Diversification distance
Occupant Comfort	Front legroom	42.3	42.3	42.2	0.1
	Rear legroom	37	37	38.9	1.9
	Front headroom	38.7	38.7	39.8	1.1
	Rear headroom	37.8	37.8	36.7	1.1
	Front hip room	54	54	54.5	0.5
	Rear hip room	53.4	53.6	55.7	2.3
	Front shoulder room	57.4	57.4	57.3	0.1
	Rear shoulder room	56.5	55.6	56.6	1.0
	Passenger volume	100	100	102	2.0

Table 4.3: Function Attributes Diversification Distance

Afterward, each aattribute Distance Ratio is calculated by comparing the two values to the overall distance for each attribute, the front legroom function attribute values are calculated:

Attribute Distance Ratio (*adr*) $(P_{i,a}, P_{i,b}, b_l^i) = \frac{|43.3-42.3|}{0.1} = 0.0$

Attribute Distance Ratio (*adr*) $(P_{i,b}, P_{i,c}, b_l^i) = \frac{|42.3-42.2|}{0.1} = 1.0$

Attribute Distance Ratio (*adr*) $(P_{i,a}, P_{i,c}, b_l^i) = \frac{|42.3-42.2|}{0.1} = 1.0$

Function	Function attribute	Attribute Distance Ratio A & B	Attribute Distance Ratio A & C	Attribute Distance Ratio B & C
Occupant Comfort	Front legroom	0.0	1.0	1.0
	Rear legroom	0.0	1.0	1.0
	Front headroom	0.0	1.0	1.0
	Rear headroom	0.0	1.0	1.0
	Front hip room	0.0	1.0	1.0
	Rear hip room	0.1	1.0	0.9
	Front shoulder room	0.0	1.0	1.0
	Rear shoulder room	0.9	0.1	1.0
	Passenger volume	0.0	1.0	1.0

Table 4.4: Function Attribute Distance Ratio

Taking the sum of all *adr* for each function, over the number of function attributes of the function, which is 9 attributes, in the function, we find the Function Distance Ration (*fdr*) :

$$fdr(P_{i,a}, P_{i,b}, f_t) = \frac{1}{9} \sum_{l=1}^{9} \frac{|U_1^t(i,a) - U_1^t(i,b)|}{\Delta\ b_1^t} = \frac{0.99}{9} = 0.11$$

$$fdr(P_{i,a}, P_{i,c}, f_t) = \frac{1}{9} \sum_{l=1}^{9} \frac{|U_1^t(i,b) - U_1^t(i,c)|}{\Delta\ b_1^t} = \frac{8.1}{9} = 0.9$$

$$fdr(P_{i,b}, P_{i,c}, f_t) = \frac{1}{9} \sum_{l=1}^{9} \frac{|U_1^t(i,b) - U_1^t(i,c)|}{\Delta\ b_1^t} = \frac{8.91}{9} = 0.99$$

Function	Function attribute	Function Distance Ration A & B	Function Distance Ration A & C	Function Distance Ration B & C
Occupant Comfort	Front legroom	0.11	0.90	0.99
	Rear legroom			
	Front headroom			
	Rear headroom			
	Front hip room			
	Rear hip room			
	Front shoulder room			
	Rear shoulder room			
	Passenger volume			

Table 4.5: Function Distance Ration

Per equation, the *fdr* = Zero only if all functions attributes of $f_t$carry the save values in all platforms, by agreement$1 \geq fdr \geq 0$. The biggest distance gap is between product A and product C most of the function attributes between A and B and close and similar in most cases.

4.2.1.1 Standard Platform Differentiation Function Analysis (PDFAs)

To analyze the Platform Differentiation Score for standard functions (PDSs), we assign:

$\mathcal{F}_{(i,\, a+b)}$: Sum of all functions available in both $P_{i,a}$ and $P_{i,b}$

$\mathcal{F}_{(i,\, b+c)}$: Sum of all functions available in both $P_{i,b}$ and $P_{i,c}$

By calculating the function distance ratio for both common and marketable functions in the PDFAs,

$$PDFAs_1(P_{i,a}, P_{i,b}) = \sum_{\substack{f_t available\ in \\ (P_{i,a}, P_{i,b})}} fdr\big(f_t, P_{i,a}, P_{i,b}\big)$$

$$= 0.11 + .33 + 0.32 + 0.1 + 0.2 + 0.04 = \ \ 1.181$$

$$PDFAs_2(P_{i,a}, P_{i,c}) = 9.775 \quad , \qquad PDFAs_3(P_{i,b}, P_{i,c}) = 9.727$$

4.2.1.2 Exclusive Platform Differentiation Functions Analysis (PDFAe)

Considering exclusive functions in the PDI for the given P_a P_b, P_c, we assign:

$\mathcal{F}_{(i,\, a|b)}$: Sum of exclusive functions available in $P_{i,a}$ or $P_{i,b}$

$\mathcal{F}_{(i,\, b|c)}$: Sum of exclusive functions available in $P_{i,b}$ or $P_{i,c}$

Therefore, the exclusive functions analysis can be found by:

$$PDFAe_1(P_{i,a}, P_{i,b}) = \mathcal{F}_{(i,\ a|b)} = 1,$$

$$PDFAe_2(P_{ia}, P_{i,c}) = \mathcal{F}_{(i,\ a|c)} = 1$$

$$PDFAe_3(P_{i,b}, P_{i,c}) = \mathcal{F}_{(i,\ b|c)} = 1$$

By considering all platform different functions, common and exclusive, we now can calculate the platform diversification index (PDI) by:

$$PDI(P_{i,a}, P_{i,b}) = \frac{PDFAs_1(P_{i,a}, P_{i,b}) + PDFAe_1(P_{i,a}, P_{i,b})}{\mathcal{F}_{(i,\ a|b)} + \mathcal{F}_{(i,\ a+b)}}$$

$$PDI(P_{i,a}, P_{i,}) = \frac{1.181 + 1}{1 + 19} = 0.109$$

$PDI(P_{i,a}, P_{i,c}) = 0.539,$ $PDI(P_{i,b}, P_{i,c}) = 0.558$

$PDI(P_{i,a}, P_{i,b})$ Calculates the initial diversification between any two platforms. The second step is to understand the diversification of any platform in relationship to the rest of the platforms within or between product families. Given$PDI(P_{i,b})$, we calculate the average of all $PDI(P_{i,b})$ for every $(P_{i,b})$ in the family

$$PDI_{F_i}(P_{i,a}) = \frac{1}{(F_N - 1)} \sum_{P_{i,c,a} \in F_{i,}\ b \neq a, \neq c} PDI(P_{i,b}, P_{i,a}), PDI(P_{i,b}, P_{i,c})$$

$PDI\ (P_a) = \frac{0.324}{(3-1)} = 0.162,$ $PDI(P_b) = 0.167$ $PDI(P_c) = 0.274$

Where $F_N$is the number of product platforms involved in platform diversification index

Production volume for model year 2006 has been selected randomly, as shown in table 4.1

The Platform Efficiency Power PE_p in the market shares of any given platform in relationship to other platforms can be achieved by:

$$EP_p(P_a) = \left(PDI_{F_i}(P_{i,b})\right) * (\% \ M_s \left(P_{i,b}\right))$$

$$EP_p(P_a) = 89.12 * 0.162 = 14.432$$

$$EP_p(P_b) = 1.8157$$

$$EP_p(P_c) = 1.6911$$

Vehicle model Ford Fusion has the most efficient power among all three vehicle models. Therefore, the Dominated product Platform (D_p) for an enterprise to maintain with respect to profit and market share can be achieved by:

$$D_{p(P_a)} = \left(\frac{P_a}{\text{Max } PE_p}\right) * 100$$

$$D_{p(P_a)} = \frac{14.432}{14.432} * 100 = 100\% \ Domination$$

$$D_{p(P_b)} = 12.582 \ \% \ Domination$$

$$D_{p(P_c)} = 11.718 \ \% \ Domination.$$

The dominated product model is the strongly recommended model to maintain and develop in the enterprise as it has the highest market share among others. Any changes in the function attribute values will affect the domination percentage outcome. Nevertheless, adding more exclusive functions to any product model will impact the domination percentage significantly.

4.2.2 Families Diversification Index (FDI)

The Families Diversification Index (FDI) is a continuation of the optimization process following the Product Diversification Index (PDI). The PDI has the capability to optimize product platforms and suggest recommendations to what vehicles should be kept in production, and which are suggested to be discontinued from the market. PDI is applied across all product families, as addressed previously. The next step is to optimize product families with the recommended product platforms.

In 2006, the selected OEM manufactures three different product families, Ford, Lincoln, and Jaguar. Production volumes for all three product families along with associated product platforms for each family are illustrated in table 4.6

	Ford Motor Company (MY 2006 Production Volume)					
	Ford		Lincoln		Jaguar	
Platform	Vehicle	Volume	Vehicle	Volume	Vehicle	Volume
	Ranger	100,070	MKZ	331,14	X Type	29,394
	Escape	208,998	Navigator	23,947	XJ	9,972
	Focus	879,752	MKX	859	S Type	16,674
	Freestar	52,302	LS	8,797	XK	11,951
	F Truck	856,508	Mark LT	12,753		
	expedition	92,416	Town Car	39,295		
	Taurus	174,124				
	Thunderbird	5,621				
	Explorer	197,190				
	Fusion	316,096				
	Mustang	178,365				

Table 4.6: Ford Motor Co. - MY 2006 Production Volume

The production volume gap between one family and the other two families is significantly big. Figure 4.3 shows the significant gap between Ford product family and the other two families. The OEM has to make an executive decision to reduce validation cost and resources allocated to each product families.

An optimization model is required to assist in the decision making without any sacrifice in the market share, even increasing the market share with least cost and expenses.

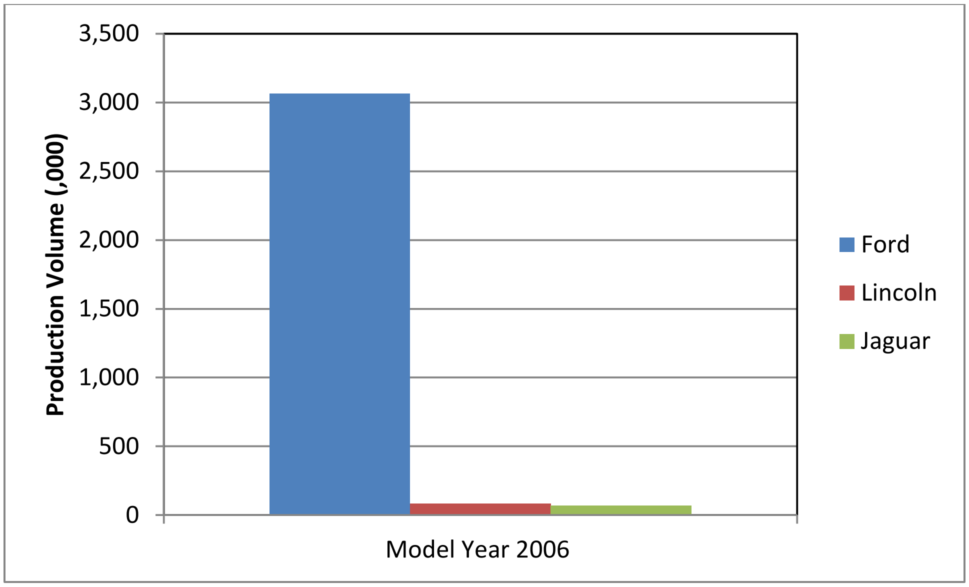

Figure 4.3: Ford Motor Co. - MY 2006 Production Volume

All three families are subjected to an extensive review of all features, functions, function attributes, and values for each attribute. The applied clustering method of all functions is very similar to the product platform clustering. The two main categories are 1) Standard Functions, and 2) exclusive functions. Categorization of functions are kept in the same flow as shown in table 4.3

The given product families F_a, $F_{b,}$ and F_c refers to Ford, Lincoln, and Jaguar product family consecutively. Functions in all three families are classified for analysis in the following two sections.

4.2.2.1 Exclusive Family Differentiation Function Analysis (FDFAe)

Exclusive functions are considered to be available in one product family only, or are considered to be a big marketing hit in the industry to attract customers and end-users. For example, an engine offers a power function to the vehicle. However, a hybrid engine serve the same function, but is considered to be a very high attracted feature to consumers. The exclusive functions count only functions availability without breaking down functions into attributes and values. Exclusive functions data is collected and classified as shown in Appendix I-B

In the exclusive function analysis, for each function F_t in every product family, as defined in table x4.3, we calculate family efficiency and deficiency scores for each product family:

The Exclusive Family Efficiency Score (FESe) for Ford family (F_a) is calculated by adding all FESe of (F_a) against Lincoln family (F_b) and Jaguar(F_c):

$$= \sum_{f_t \in F_{(a-b)}} \frac{R_t^{a-b}}{L_t} + \sum_{f_t \in F_{(a-c)}} \frac{R_t^{a-c}}{L_t}$$

	Functions	R_t^{a-b}/L_t	R_t^{a-c}/L_t
exclusive functions/marketable	Hitch back door	1.00	2.00
	4 X4 Drive	0.00	1.00
	Driving Assistance / GPS	0.00	0.00
	Hybrid Engine	0.00	1.00
	Heavy duty	1.00	2.00
	Open Roof - Convertible	0.67	0.60
	Pick-up with double cabinet-Crew Cab	0.00	1.00
	Wagon	0.50	0.00
	low end class	1.00	11.00
	High-End Class	0.00	0.00
	Segment	0.50	1.20
	Total	4.67	19.8

Figure 4.4: FESe for Ford Product Family

Therefore: FESe (F_a) = 4.67 + 19.8 = 24.47

FESe (F_b) = 1.27 + 1.53 = 2.8

FESe (F_c) = 0.33 + 2.0 = 1.17

And the Exclusive Family Deficiency Score (FDSe) for Ford family (F_a) is calculated in the method, but in a negative outcome. The negative is due the functions that are offered in other families but (F_a).

Therefore, the FDSe is calculated by:

$$= - \sum_{f_t \in F_{(b-a)}} \frac{R_t^{b-a}}{L_t} - \sum_{f_t \in F_{(c-a)}} \frac{R_t^{c-a}}{L_t}$$

	Functions	R_t^{b-a}/L_t	R_t^{c-a}/L_t
exclusive functions/marketable	Hitch back door	0.00	0.00
	4 X4 Drive	0.00	0.00
	Driving Assistance / GPS	-0.67	-0.33
	Hybrid Engine	0.00	0.00
	Heavy duty	0.00	0.00
	Open Roof - Convertible	0.00	0.00
	Pick-up with double cabinet-Crew Cab	0.00	0.00
	Wagon	0.00	0.00
	low end class	0.00	0.00
	High-End Class	-0.6	-.4
	Segment	0.00	0.00
	Total	- 1.27	- 0.73

Figure 4.5: **FDSe for Ford Product Family**

Therefore,

Exclusive Family Deficiency Score for each family verses others, are:

FDSe (F_a) = -1.27-0.73 = -2.0

FDSe (F_b) = -0.83 – 4.67 = -5.5

FDSe (F_c) = - 19.8 – 2.03 = -21.83

A quick analysis of exclusive function among the three studied families, the base case study clear identifies the recommended product families.

A Ford product family earns 22.47 point, Lincoln product family earns negative points of (-2.7), and Jaguar loses (-20.66). Both Lincoln and Jaguar do not offer significant exclusive functions that are not partially or mainly covered by Ford product family.

4.2.2.2 Standard Family Differentiation Function Analysis (FDFAs)

The Standard Family Differentiation Function Analysis (FDFAs) investigates the standard functions in more depth. Functions attributes and their values are analyzed to understand the gap between product families. Some attributes contain actual values by design, and others do not. Values for quantitative attributes are assigned by either designer or by the market demand. Usually, quantitative attribute values ears basic point to availability by assigning number one to it, or assigning number zero if not available.

Data, functions, function attributes, and values are collected and presented in Appendix I-A. Considering all standard and marketable functions available between evaluated product families, attributes are classified to be either efficient or deficient. Efficient attribute is an attribute that is available and repeated within the product family across platforms more than other families. Deficient attributes are where attributes are offered in product families other than the product family under analysis.

Standard functions shared among all three product families in the case studies. Occupant function is one of the most important functions in any vehicle. And the attributes associated to this function are shown in table 4.7

We assign $\mathcal{F}\, F_{(a+b+c)}$ as set of functions available in F_a and F_b and F_c to calculate the Attribute Efficiency Score (AESs):

$$f = \begin{cases} \theta^{t}_{l,i} > \vartheta^{t}_{l,i},\ \theta^{t}_{l,i} > \delta^{t}_{l,i}, & function\ is\ available \\ 0, & othersie \end{cases}$$

$$(f_t, b^{t}_{l}, F_a, \rightarrow F_b, F_c) = \sum_{\substack{i=1 \\ \theta^{t}_{l,i} > \vartheta^{t}_{l,i}}}^{T} \frac{(\theta^{t}_{l,i} - \vartheta^{t}_{l,i})u^{t}_{l,i}}{u^{\mathrm{t}}_{\mathrm{l,T}} - u^{\mathrm{t}}_{l,1}} + \sum_{\substack{i=1 \\ \theta^{t}_{l,i} > \delta^{t}_{l,i}}}^{T} \frac{(\theta^{t}_{l,i} - \delta^{k}_{l,i})u^{t}_{l,i}}{u^{\mathrm{t}}_{\mathrm{l,T}} - u^{\mathrm{t}}_{l,1}}$$

And

Attribute Deficiency Score (ADSs) =

$$f = \begin{cases} \theta^t_{l,i} < \vartheta^t_{l,i},\ \theta^t_{l,i} < \delta^t_{l,i}, & function\ is\ available \\ 0, & othersie \end{cases}$$

$$(f_t, b^t_l, F_a, \to F_b, F_c) = -\left[\sum_{\substack{i=1 \\ \theta^t_{l,i} < \vartheta^t_{l,i}}}^{T} \frac{(\theta^t_{l,i} - \vartheta^t_{l,i})u^t_{l,i}}{u^t_{l,T} - u^t_{l,1}} + \sum_{\substack{i=1 \\ \theta^t_{l,i} < \delta^t_{l,i}}}^{T} \frac{(\theta^t_{l,i} - \delta^k_{l,i})u^t_{l,i}}{u^t_{l,T} - u^t_{l,1}} \right]$$

Functions	Function attribute	Number of Attributes	Ford Product Family	
Occupant Comfort	Front legroom	13	279	-1783
	Rear legroom		12.42	-2.84
	Third row legroom		2.9	0
	Front headroom		189.52	-36.15
	Rear headroom		15.36	-2.9
	third row headroom		3.0	0
	Front hip room		18.12	-4.34
	Rear hip room		15.17	-5.17
	Third row hip room		3.8	-0.8
	Front shoulder room		91.43	-22.35
	Rear shoulder room		15.07	-4.48
	third row shoulder room		3.7	-0.9
	Passenger volume cu. Ft		17.48	-5.69

Table 4.7: Occupant Comfort Function attributes

By calculating the Occupant Comfort function attribute values for Ford product family verses Lincoln and Jaguar, we find:

Attribute Efficiency Score (AESs) = 149.02

Attribute Deficiency Score (ADSs) = - 86.76

Both efficiency and deficiency scored is calculated for all product families across all functions.

Adding all function efficiency score over the total number of shared standard functions, and the Family Efficiency Scored for standard functions (FESs) is achieved by:

Family Efficiency Score for standard functions (FESs) =

$$\frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs} \left(f_t, b_l^t, F_a, \rightarrow F_b, F_c \right) \right]$$

Where T_t represents the total number of function attributes in each function.

Family Deficiency Scores for standard functions (FDSs) =

$$-\frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs} \left(f_t, b_l^t, F_a, \rightarrow F_b, F_c \right) \right]$$

By substituting values, we find the family advantage and disadvantage for standard functions:

Ford product family:

Family Efficiency Score for standard functions (FESs) = 22.59

Family Deficiency Scores for standard functions (FDSs) = -4.27

Lincoln Product family:

Family Efficiency Score for standard functions (FESs) = 9.37

Family Deficiency Scores for standard functions (FDSs) = -10.97

Jaguar Product family:

Family Efficiency Score for standard functions (FESs) = 5.32

Family Deficiency Scores for standard functions (FDSs) = -17.7

The Family Diversification Index is the sum of all previous equation for standard and exclusive functions

Exclusive Family Efficiency Score (FESe) + Exclusive Family Deficiency Score (FDSe) + Standard Family Efficiency Score (FESs) + Standard Family Deficiency Score (FDSs) + # of product platform

FDI =

$$\left\{ \sum_{f_t \in F_{(a-b)}} \frac{R_t^{a-b}}{L_t} - \sum_{f_t \in F_{(b-a)}} \frac{R_t^{b-a}}{L_t} + \frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_c) \right] - \frac{1}{\boldsymbol{F}_{\boldsymbol{F}(a+b+c)}} \sum_{f_t \in F_{(a-(b,c))}} \left[\frac{1}{T_t} \sum_{t=1}^{T_t} \text{AESs}\,(f_t, b_l^t, F_a, \rightarrow F_b, F_c) \right] + \#\, of\ product\ platforms \right\}$$

Family Diversification Index (FDI) – Ford = 48.28

Family Diversification Index (FDI) – Lincoln = 3.57

Family Diversification Index (FDI) – Jaguar = -27.41

The FDI is and evaluation index to identify strengths and weaknesses of a product family within an enterprise, or competitors in the same industry. FDI optimizes product families and furniture executives and corporate decision makers to identify families with most functions and features. However, market share has a significant impact on profit. Therefore, market shares need to be considered in the optimization process.

Ford, Lincoln, and Jaguar manufactured and sold vehicles in NA for Model Year MY 2006, and along with their market shares M_s are shown in table 4.8

	Product Family		
	Ford	Lincoln	Jaguar
Model Year 2006	3,055,821	118,765	67,991
Market Share %	94.3	3.66	2.1

Table 4.8: Product Family Production Volume - MY 2006

Knowing the family index and the market share for every family help to calculate the power of the family efficiency, this can be calculated by:

$$FE_p = (FDI \ * (\% \ M_s \ )$$

Therefore,

$EP_{(F_a)} = \left(FDI_{a)} \ * (\% \ M_{s_{(F_a)}} \ \right)$ = 4550.30

$EP_{(F_b)} = \left(FDI_{(F_b)} \ * (\% \ M_{s_{(F_b)}} \ \right)$ = 13.06

$EP_{(F_c)} = \left(FDI_{(F_b)} \ * (\% \ M_{s_{(F_b)}} \ \right)$ = -57.47

A quick evaluation of each family efficiency power, Jaguar is Cleary identified with no efficiency and it should be discontinued from the market. At the same time, Lincoln family is very close to lose its efficiency if no further action is taken to survive.

The Dominated Product Family D_f among all three product family is calculated by:

$$D_{f(F_i)} = \left(\frac{F_i}{\text{Max } FE_p}\right) * 100$$

$D_{f(a)}$ = 100 % domination, $D_{f(b)}$ = 0.3 % domination, $D_{f(c)}$ = -1.26 % domination

4.2.3 Family Saturation Index (FSI)

The Family Saturation Index (FSI) investigates on how (F_a) is saturated with functions and function attributes available in the sum of other families (F_{N-a}). Following the assumption presented in section 3.9, let F_t be a function available in all (F_a) and (F_{N-a}), and b_l^t be a function attribute. Let $\boldsymbol{U}_l^{\mathrm{t}} = (\boldsymbol{u}_{l,1}^{\mathrm{t}}, \boldsymbol{u}_{l,2}^{\mathrm{t}}, .. \boldsymbol{u}_{\mathrm{l,T}}^{\mathrm{t}})$ represent all possible values for each function attribute b_l^t in every function F_t, and T represent number of values in each attribute. $\theta_{l,i}^t$ and $\vartheta_{l,i}^t$ are assigned as the number of repeatability of each function in F_a , and (F_{N-a}) (respectively).

By equation 3.15, and Table 4.4,

Attribute Saturation Score (ASS) =

$$\left(f_t, b_l^t, F_a, (F_{N-a})\right) = \frac{1}{T} \sum_{\vartheta_{l,i}^k > 0} MAX\left(1, \frac{\theta_{l,i}^t}{\vartheta_{l,i}^t}\right)$$

We calculate the Attribute Saturation Score (ASS) for every attribute within the same functions.

The front legroom attribute ASS is calculated as:

$$(front\ letroom\ ASS) = \frac{1}{9} \sum_{\vartheta_{l,i}^k > 0} (2 + 1 + 1 + 1 + 1 + 11 + 1 + 1 + 1 + 2) = 1.44$$

And the occupant comfort saturation level is calculated by

$$\sum_{f_t \in F_a, (F_{N-a})} [1.44 + 1.78 + 1.5 + 1.7 + 2 + 1.5 + 1.25 + 2.67 + 2 + 1.9 + 1.9 + 2 + 2]$$

= 1.895

Functions	Function attribute	$\frac{\theta_{l,i}^{t}}{\vartheta_{l,i}^{t}}$	$MAX\left(1,\frac{\theta_{l,i}^{t}}{\vartheta_{l,i}^{t}}\right)$	T = $\vartheta_{l,i}^{k} > 0$	$\sum_{\vartheta_{l,i}^{k}>0} MAX\left(1,\frac{\theta_{l,i}^{t}}{\vartheta_{l,i}^{t}}\right)$	ASS
Occupant Comfort	Front legroom	2	2	9	13	1.44
	Rear legroom	0	1	9	16	1.78
	Third row legroom	.9	1	2	3	1.5
	Front headroom	0	1	10	17	1.7
	Rear headroom	0	1	9	18	2
	third row headroom	1	1	2	3	1.5
	Front hip room	0	1	8	18	2.25
	Rear hip room	0	1	6	16	2.67
	Third row hip room	1	1	2	4	2.0
	Front shoulder room	0	1	10	19	1.9
	Rear shoulder room	0	1	10	19	1.9
	third row shoulder room	1	1	2	4	2.0
	Passenger volume cu. Ft	0	1	9	18	2.0

Table 4.9: Occupant Comfort Saturation Index

To calculate the Family Saturation Index (FSI) for (F_a) against all other product families, we substitute in equation 3.6:

$$\frac{1}{\boldsymbol{F}_{\boldsymbol{F_a}+(\boldsymbol{F_{N-a}})}} \sum_{f_t \in F_a,(F_{N-a})} \left[\frac{1}{T_t}\sum_{t=1}^{T_t} \mathrm{ASS}\left(f_t, b_l^t, F_a, (F_{N-a})\right)\right] \qquad (3.16)$$

Family Saturation Index (FSI) =

$$\frac{\begin{matrix}1.9+2.09+1.6+2.58+1.98+2.05+\\1.55+2.05+2.88+2+1.33+\\1.67+2.03+2.11+2.06+\\2.33+2.5+2.311\end{matrix}}{20} = 2.04$$

Conducting same process, we calculate the FSI for the rest of other families:

Ford Product Family (FSI) = 204%

Lincoln Product Family (FSI) = 115%

Jaguar Product Family (FSI) = 113%

A value with more than 100% saturation level indicates that the family offer redundant functions and function attributes. The ultimate saturation level for an enterprise to be healthy is in the range between 90%-100%. Ford family manufactures vehicles with high redundancy, and covers and exceeds all functions offer in the other two families

4.2.4 Family Unsaturation Index (FUI)

As described previously, the unsaturation index needs to be calculated to understand what functions and function attributes are available in other families, but not in the evaluated family. For simplicity, let the target family to be (F_a), and (F_{N-a}) as the set of all other product families.

4.2.4.1 Exclusive Function Unsaturation Score (FUSe)

We donate $\mathcal{F}(\,(F_{N-a}) - F_a)$ for functions available in all product families (F_{N-a}) but not in (F_a). Functions available in all product families but not in (F_a), we assign($(F_{N-a}) - F_a)$.

The Exclusive Function Unsaturation Score (FUSe) ($F_{N-a}), F_a$ is calculated by:

$$\frac{1}{total_f^{a+(N-a)}} \sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a})$$

	Functions	# of Function repeatability in (F_a)	# of Function repeatability in $\sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a})$	$total_f^{a+(N-a)}$	FUSe
Exclusive functions/marketable	Hitch back door	2	0	51	0
	4 x4 drive	4	4	51	0.078
	Driving assistant / GPS	0	3	51	0.058
	Hybrid engine	1	1	51	0.019
	Heavy duty	2	0	51	0
	Open roof - convertible	2	1	51	0.019
	Pick-up W/ double cabin	1	1	51	0.019
	Wagon	1	1	51	0.019
	Low end class	11	0	51	0
	High-end class	0	10	51	0.196
	Unique platform segment	4	2	51	0.039

Table 4.10: Function Saturation Score per Function

From table 4.10, we clearly observed that some functions Hitch back door carries a weight of 0%, which means that 0% unsaturation index. On the other hand, the High-end class has 19% unsaturation index. Family (F_{N-a}) has 19% higher index than (F_a) in this function, as a whole.

4.2.4.2 Standard Function Unsaturation Score (FUSs)

The unsaturation score needs to be calculated to have a better understating of unsaturation level. Let b_l^t be a function attribute of F_t. Let $\boldsymbol{U}_l^{\mathrm{t}} = (\boldsymbol{u}_{l,1}^{\mathrm{t}}, \boldsymbol{u}_{l,2}^{\mathrm{t}}, .. \boldsymbol{u}_{\mathrm{l,T}}^{\mathrm{t}})$ be all possible values assigned to b_l^t in all product families in the same function. In addition, we donate $\theta_{l,i}^k, \vartheta_{l,i}^k$ as the number of repeatability of F_t in (F_a) and (F_{N-a}) (respectively).

A deep dive analysis is conducted on function attributes level for each in the standard functions, and then further analysis is calculated on function level.

To analyze the Front Legroom function attribute in the Occupant Comfort Function, values from table 4.11 are substituted in equation 3.18 for calculation.

Functions	Function attribute	possible values U_l^t	$u_{l,1}^t, u_{l,2}^t, .. u_{l,T}^t$	# of repeatability in (F_a)	# of repeatability in (F_{N-a})	$\sum_{\substack{i=1 \\ \theta_{l,i}^t=0}}^{T} (\vartheta_{l,i}^t)$	$\sum_{i=1}^{T}(\theta_{l,i}^t - \vartheta_{l,i}^t))$	AUSs
Occupant Comfort	Front legroom	11	42.4	2	1	0	3	0.19
			43.1	0	2	2	2	
			43	0	1	1	1	
			42.8	0	1	1	1	
			42.7	2	0	0	2	
			42.3	1	1	0	2	
			42.2	1	0	0	1	
			41.6	1	1	0	2	
			41.3	1	1	0	2	
			41.2	1	1	0	2	
			40.7	2	1	0	3	

Table 4.11: Front Legroom Function Attribute Unsaturation Score

Standard Attribute Unsaturation Score (AUSs) =

$$\left(f_t, b_l^t, F_a, F_{(N-a)}\right) = \frac{\sum_{\substack{i=1 \\ \theta_{l,i}^t=0}}^{T} \left(\vartheta_{l,i}^t\right)}{\sum_{i=1}^{T}(\theta_{l,i}^t - \vartheta_{l,i}^t)}$$

The rest of all other function attributes within the same function are calculated I the same manner. And they are shown in table 4.12

Functions	Function attribute	AUSs
Occupant Comfort	Front legroom	0.190476
	Rear legroom	0.285714
	Third row legroom	0
	Front headroom	0.3
	Rear headroom	0.35
	third row headroom	0
	Front hip room	0.428571
	Rear hip room	0.388889
	Third row hip room	0.047619
	Front shoulder room	0.45
	Rear shoulder room	0.428571
	third row shoulder room	0.047619
	Passenger volume cu. (Ft)	0.333333

Table 4.12: Occupant Comfort Function Attributes Unsaturation Score

After calculating the function attribute score for each and every function, additional analysis is conducted to calculate the unsaturation on function level Unsaturation Score on Function level by applying equation 3.19. The Standard Functions Unsaturation Score (FUSs) is calculated as shown in table 4.13

Now, we now the unsaturation scores for both standard and exclusive functions.

To calculate the overall family (F_a) unsaturation level against all other families (F_{N-a}), we substitute in equation 3.2

The Family Unsaturation Index (FUI) =

$$\frac{1}{2}\left[\frac{1}{total_f^{a+(N-a)}} \sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a}) + \frac{1}{\boldsymbol{F_a} + \boldsymbol{F_{(N-a)}}} \sum_{f_t \in F_{(a+N-a)}} \frac{1}{T_t} \sum_{t=1}^{T_t} \text{AUSs}\,(f_t, b_l^t, F_a, F_{N-a})\right]$$

$$= \frac{1.0.225+0.078+0.058+0.019+0.019+0.019+0.019+.0196+0.03}{2} = 0.225*100 = 22.5\%$$

Functions	Function un-coverage Score	Standard Functions Unsaturation Score (FUSs)
Seating	0.057	0.133
Occupant Comfort	0.250	
Entertainment	0.066	
Safety	0.038	
Security	0	
Ventilation	0	
Exterior Dimensions	0.333	
Engine	0.171	
Fuel Economy	0.238	
Auto Transmission	0.190	
slide breaking	0	
Drive Type	0	
Power mechanism	0	
Acceleration	0.276	
Handling	0.350	
luggage volume	0.428	
Tire	0.238	
Access to vehicle	0	
pickup box	0.031	

Table 4.13: Standard Function Unsaturation Score Calculation

The (F_a) family saturation and unsaturation index has been calculated. By following the same process and mathematical equation, both scores are computed and results are shown in the table below.

Family	**Family Saturation Index %**	**Family Unsaturation Index %**
Ford Family against Lincoln and Jaguar families	204.06	22.55
Lincoln Family against Ford and Jaguar families	115.08	35.29
Jaguar Family against Ford and Lincoln families	113.39	42.16

Table 4.14: Families Scores Comparison

A quick overview of the saturation index level and the unsaturation index level, the outcomes are clearly shown. The Ford product family has a 204.06% saturation level. Which mean, Ford product family includes all functions and function attributes offered in

Lincoln and Jaguar product families; not only this, function attributes are offered twice within the Ford family. In contrast, Lincoln and Jaguar product families carry 22.55% more function and function attributes than Ford family. This unsaturation index in Ford product family considered to be deficiency.

Same analytical analysis applies on the rest of the product family - Lincoln Family against Ford and Jaguar families - , and - Jaguar Family against Ford and Lincoln families. Both Lincoln and Jaguar have almost the same saturation index level, which indicates that they offer all functions and function attributes that are available across the three product families, with least redundancy. This percentage considered to be the ultimate percentage to offer all functions to the end-user.

If the case study is dedicated only on saturation level, we would recommend Ford family to reduce the saturation index level, and replace the redundant functions with more unique and marketable functions. However, the case study takes the family diversification index into consideration, which will be discussed in more depth in the next section.

4.3 Analysis validation and recommendations

The case study goal is to evaluate the Ford Motor Company Product Families and Product Platforms production in for calendar year 2006. The analysis evaluated all functions and function attributes offered during that period of time, as illustrated in appendix H and I.

Increasing the family diversification index indicates that adding a new function, or modifying an existing function or function attributes will differentiate the family among others. Product family differentiation is what makes family unique and stand solid among other product family. Even within the same enterprise.

As illustrated in table 4.15, ford product family shows a very high significant diversification index in comparison with Lincoln and Jaguar product family. In contrast, Jaguar does not really offer any diversifications in its product family. Therefore, the index has been calculated to be negative. Negative divarication index should be a strong indication to the executive management in the enterprise to either; eliminate the product family from the market or modify the product to offer some unique functions to the end-user.

Family	Family Diversification Index	Family Saturation Index (%)	Family Unsaturation Index %
Ford Family against Lincoln and Jaguar families	40.57	204.06	22.55
Lincoln Family against Ford and Jaguar families	6.87	115.08	35.29
Jaguar Family against Ford and Lincoln families	-31.95	113.39	42.16

Table 4.15: Ford Motor Company Analysis

The situation of Ford Motor Company currently validates the outcomes of the proposed model. Ford executive made some wise decisions and modified the product family portfolio and fleet line. Jaguar product family has been sold out Tata Corporation. Jaguar product family did not offer any unique and significant functions to the market. Nevertheless, lack of unique functions offered to the market in any product family lead to low sales in volume.

In addition, the family saturation index indicates and identifies the redundant functions within the family. Ford families not only offered all functions available in Lincoln and Jaguar families, but double the functions and their attributes. The 204% index in saturation level means that some functions were offered in many product platforms. Redundancy in functions and extreme standardization is not highly recommended. Consumers tend to lose loyalty and confidence in the brand as all functions are identical, regardless of the product platform.

The analysis directs and assist executive to make the following decision:

1- Modify Jaguar product family functions and function attributes, or eliminate the entire family from the market.
2- Ford product family carries significant number of redundant functions and function attributes. Most of the functions could be eliminated without jeopardizing the market share.
3- Ford product family is short on some functions and function attributes that are offered in Lincoln and Jaguar families.
4- Ford family has the opportunity to revise their design and offer more functions.
5- Lincoln product family has the opportunity to increase it is diversification index to adopt and accommodate all Jaguar functions, after eliminating Jaguar family from the market.
6- Lincoln and Ford families have the opportunity to gain more market share by moving Jaguar customers over their sides.

The case study evaluated Ford Motor Corporation situation in the market during calendar year 2006, the outcomes of the analysis should match and concur with the company current situation for calendar year 2012 (Model Year 2013)

According to the analysis recommendations, Jaguar product family should be discontinued from the market, which will not affect the overall market shares.

Ford Motor Company Production Volume (,000)							
	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Ford Family	3,141	2,614	1,911	1,821	1,889	2,124	2,179
Lincoln Family	110	131	107	83	86	86	82
Jaguar Family	19	15	14	0	0	0	0
Ford Mo. Co. Market Share	16.04	14.59	14.19	15.29	16.44	16.48	16.51
NA total production	15,877	15,426	12,922	8,761	12,156	13,478	15,798

Table 4.16: Ford Motor Company Production Volume

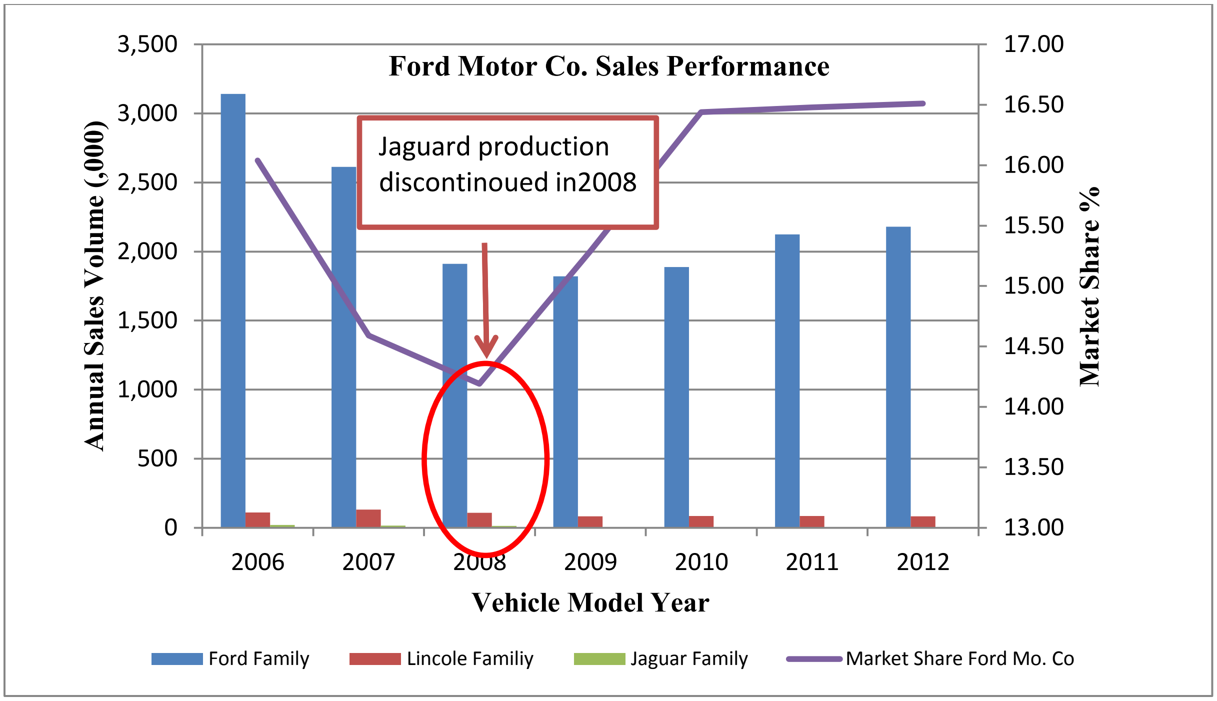

Figure 4.6: Ford Motor Co. Sales Performance

Sure enough, Jaguar product family was sold to Tata Motors in year 2008. The date illustrated in figure 4.6 is self-explanatory, as Ford market share stating flying up north and increased almost by 20%. Loyal customers to Ford Motor Company did not move away, Ford and Lincoln product families incorporated Jaguar functions and function attributes into their products. Ford introduced new designs and options to their fleet to maintain or even increase the market share.

The proposed mathematical model is well validated and proven right in the case study of Ford Motor Company. The next step is to analyze a different case study from the automotive industry from current status, and make recommendations for future strategy. The next case study will evaluate General Motors situation, including product platforms, product families, available functions and function attributes, to suggest and predict future directions to increase market shares.

5. CHAPTER FIVE - GM CASE STUDY

5.0 General Motors Company (GM)

General Motors Company, commonly known as GM, is an American multinational corporation with a headquartered located downtown of Detroit, Michigan, U.S.A. GM. Designs, manufactures, and distributes vehicles and service parts across the world. In addition, and due to the massive size of the corporation, GM sells financial services to its customers.

Back in year 2006, GM manufactured vehicles around the world in 37 countries, making low-end and Luxury high-end brands including: Chevrolet, GMC, Pontiac, Saturn, Buick, Cadillac, Opel, Geo, Hummer, Oldsmobile, and Saab. The massive number of product platforms and product families requires a great number of crews to control and manage customer needs. Therefore, GM employees 212,000 employees and does business in 157 countries.

General Motors led global vehicle sales for 77 consecutive years from 1931 through 2007, longer than any other automaker in the world, and is currently among the world's largest automakers by vehicle unit sales.

In year 2007 and after, GM discontinued several brands, closing Pontiac, Saturn, Hummer, Oldsmobile, and sold Opel brand to emerge from government backed Chapter 11 reorganization. In year 2010, General Motors made an Initial Public Offer to go back to Dow Jones stock market. Figure 5.1 presents the number of manufactured and sold vehicles between 1999 and 2012.

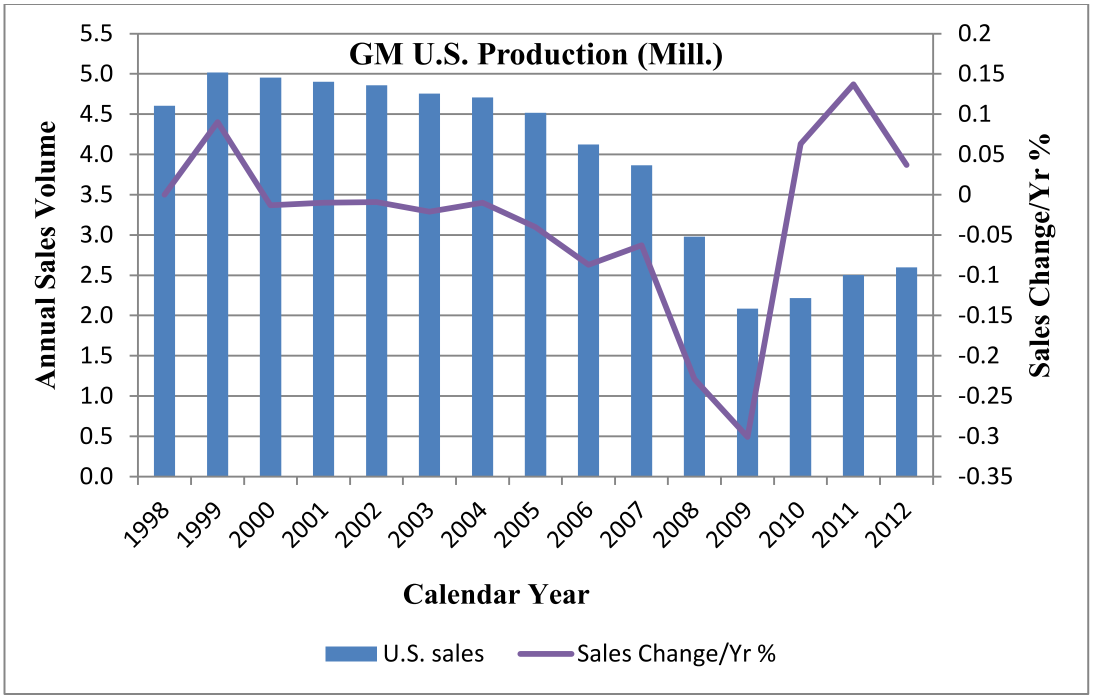

Figure 5.1: GM Product Volume in U.S.A.

5.1 Case Study Background

The proposed mathematical model will be utilized to conduct a different case study on an automotive company selected from the automotive industry. The selected case study in this chapter is General Motors. As mentioned previously. GM is considered one of the biggest automaker in the world. GM ranked top three automakers in North America for several years. This, until the European and Asian automakers started to dominate the NA market year after year. GM had no competition so several years, and the maker share in NA was unbelievable. In 2008, when the economy crisis hit the world, GM had a severe financial pain in the balance sheets, and the stock market. The daily and monthly expenses to maintain operation were unbearable; development and supply chain management cost were sky racking. GM had too many brands, product families and product platform. The unsystematic production of the vast products, without understanding the market needs and customers' expectations, led to catastrophic consequences. The consequences ended with chapter 11 declaration, unbelievable amount of stimulus loan from the government, collapse of GM shares in the stock market, and big loss of trust from investors.

Without any doubt, GM generated self-competition within itself, across the product families. GM realized the situation to some extent and sold/discontinued some of the product family, and added more functions and function attributes to its fleet to regain end-user confidence.

Currently, after selling and discontinuing several product families, GM manufactures four different product families: GMC, Cadillac, Chevrolet, and Buick. The product platforms across the four families are inconsistent. Some families carries all different platforms to serve all market segments, some serve only family oriented segments, and some serve high-end professional segment with high income. In other words, GM flipped the coin to decide what to keep and what to eliminate from the market. Identify company products portfolio based on personal judgment and reaction does not steer the organization on the right back. Statistical data, serveries, and business models should be adopted for guidance.

The case study will analyze the remaining car models across all current product families and platforms. Functions and function attributes, market share, and other variable will be considered. The model outcomes will furnish the enterprise with recommended numbers of product family and platforms to face the unforeseen economic situations in the future.

5.1.1 Platform Diversification Index (PDI)

As described in previous sections, Platform Diversification Index (PDI) utilizes automotive vehicle platforms and market share produced by on OEM to determine the most dominated platform among others to keep in production. Recommendation to discontinue making non-dominated vehicle from the market should not jeopardize the company market share.

Table 5.2 shows the car models and product platforms variation within, and across product families. A closer look at the table, we notice that some platforms offer several car models. Chevrolet product family offers three different Full-Size SUV car models from the same platform, which eventually serves the same market segment. Possibly and most likely, functions and function attributes might not be different between the three car models. The PDI will analyze and determine if there is a value added to maintain and keep them all. Or, keep one car model to serve and satisfy the aimed market segment. Never the less, the PDI will analyze all other product platforms with multiple car models, within the same family, and across all families. This analysis does not apply if there is only one platform, such as the SRX in the Cadillac family of the Mid-Size vehicle.

Product Platform	Product Family			
	Buick	**Cadillac**	**Chevrolet**	**GMC**
subcompact-Size vehicle			Sonic	
Compact-Size Vehicle	Verano	ATS	Cruze & Volt	
Mid-Size Vehicle	Regal & LaCrosse	CTS	Malibu	
Full-Size Vehicle		XTS	Impala	
compact-Size SUV	Encore			
Mid-Size SUV			Equinox	Terrain
Full-Size SUV		Escalade	Tahoe, Suburban	Yukon
Mid-Size Crossover		SRX		
Full-Size crossover SUV	Enclave		Traverse	Acadia
Mid-Size pick-up-			Colorado	Sierra
Full-Size Pick-up			Avalanche & Silverado	
Sport Vehicle			Corvette and Camaro	

Figure 5.2 GM Product Platform per Product Family

For simplicity reason, only one platform PDI will be shown in depth and the rest follows the same methodology. The mathematical model will pick the Mid-Size vehicle platform from three different product families to calculate the PDI. Table 5.2 shows an actual production volume for calendar year 2013.

The analysis considers the same functions and function attributes listed previously in table 4.2, as well as, all functions are clustered into Standard and Exclusive functions.

Calendar Year	Mid-Size Vehicle Platform				GM
	Cadillac	Buick		Chevrolet	
	CTS	Regal	LaCrosse	Malibu	
2011	45,656	12,326	61,178	198,770	Production Volume
2012	55,042	40,144	58,474	204,808	
2013	45,979	57,076	57,076	210,951	

Table 5.1: GM Mid-Size Platform Production for 2013 CY

Four given platforms, P_a, P_b, P_c, and P_d which all share a function f_t. Each function attribute b_l^t holds a different value in each platform, $U_l^t(i,a)$, $U_l^t(i,b)$, and $U_l^t(i,c)$ respectively.

Considering one function at the time, each attribute holds a value, and the maximum difference between attribute values $\Delta\, b_l^t$ calculates the gap between all platforms, and defined by:

$$\Delta\, b_l^t = MAX_{P_{i,r}\in F_i}\{U_l^t(i,t)\} - MIN_{P_{i,r}\in F_i}\{U_l^t(i,t)\}$$

Function	Function attribute	Buick Regal (2013)	Buick LaCrosse (2013)	Cadillac CTS (2013)	Chevrolet Malibu (2013)	Diversification distance
Handling	Wheelbase - in	107.8	111.7	113.4	110.5	5.6
	Front track- in	52.4	61.7	62	62.4	10.0
	Rear track - in	62.5	62	63	61.5	1.0
	Turning radius - in	18.7	18.4	17.7	19	1.3
Fuel Economy	city mpg	25	28	18	18	10.0
	highway mpg	36	36	27	30	9.0
	weight - lb	3600	3774	3898	3555	298.0
	fuel tank - gal	15.8	15.8	18	17.5	2.2
Auto Transmission	Auto=1, Manual=0	1	1	1	1	0.0
	# of gears	6	6	6	6	0.0
luggage volume	Min volume- cu.ft.	11.1	10.9	10.5	18.6	8.1
	Max volume- cu.ft.	11.1	10.9	10.5	18.6	8.1
Tire	Radius, in.	17	17	18	16	1.0
Access to vehicle	# of Doors	4	4	4	4	0.0

Table 5.2 GM Mid-Size Vehicle Function attributes diversification distance

Then, the Attribute Distance Ratio is calculated from equation 3.2 to find the ratio between platforms on attributes level, as illustrated in table 5.3

Function	Function attribute	Buick Regal (2013)	Buick LaCrosse (2013)	Cadillac CTS (2013)	Chevrolet Malibu (2013)	Attribute Dis. Ratio - Pa & Pb	Attribute Dis. Ratio - Pa & Pc	Attribute Dis. Ratio - Pa & Pd	Attribute Dis. Ratio - Pb & Pc	Attribute Dis. Ratio - Pb & Pd	Attribute Dis. Ratio - Pc & Pd
Handling	Wheelbase - in	107.8	111.7	113.4	110.5	0.7	1.0	0.5	0.3	0.2	0.5
	Front track- in	52.4	61.7	62	62.4	0.9	1.0	1.0	0.0	0.1	0.0
	Rear track - in	62.5	62	63	61.5	0.5	0.5	1.0	1.0	0.5	1.5
	Turning radius - in	18.7	18.4	17.7	19	0.2	0.8	0.2	0.5	0.5	1.0
Fuel Economy	city mpg	25	28	18	18	0.3	0.7	0.7	1.0	1.0	0.0
	highway mpg	36	36	27	30	0.0	1.0	0.7	1.0	0.7	0.3
	weight - lb	3600	3774	3898	3555	0.6	1.0	0.2	0.4	0.7	1.2
	fuel tank - gal	15.8	15.8	18	17.5	0.0	1.0	0.8	1.0	0.8	0.2
Trans.	Auto=1, manual=0	1	1	1	1	0.0	0.0	0.0	0.0	0.0	0.0
	# of gears	6	6	6	6	0.0	0.0	0.0	0.0	0.0	0.0
luggage volume	Min volume-cu. ft.	11.1	10.9	10.5	18.6	0.0	0.1	0.9	0.0	1.0	1.0
	Max volume-cu. ft.	11.1	10.9	10.5	18.6	0.0	0.1	0.9	0.0	1.0	1.0
Tire	Radius, in	17	17	18	16	0.0	1.0	1.0	1.0	1.0	2.0
Access to vehicle	Doors	4	4	4	4	0.0	0.0	0.0	0.0	0.0	0.0

Table 5.3: GM Mid-Size Vehicle Function Attributes Distance Ratio (*adr*)

And the sum of all *adr* for each function will calculate the Function Distance Ration (*fdr*) per equation using equation 3.3, and *fdr* values are shown in table 5.4

Function	Function Dis. Ration Pa & Pb	Function Dis. Ration Pa & Pc	Attribute Dis. Ratio Pa & Pd	Function Dis. Ration Pb & Pc	Function Dis. Ration Pb & Pd	Function Dis. Ration Pc & Pd
Handling	0.59	0.81	0.68	0.47	0.31	0.76
Fuel Economy	0.22	0.93	0.57	0.85	0.79	0.43
Auto –Trans.	0.00	0.00	0.00	0.00	0.00	0.00
luggage volume	0.02	0.04	0.46	0.02	0.48	0.50
Tire	0.00	1.00	1.00	1.00	1.00	2.00
Access to vehicle	0.00	0.00	0.00	0.00	0.00	0.00

Table 5.4: GM Mid-Size Function Distance Ratio (*fdr*)

5.1.1.1 Standard Platform Differentiation Function Analysis (PDFAs)

To analyze the Platform Differentiation Score for standard functions (PDSs), we assign:

$\mathcal{F}_{(i,\, a+b)}$: Sum of all functions available in both $P_{i,a}$ and $P_{i,b}$

$\mathcal{F}_{(i,\, a+c)}$: Sum of all functions available in both $P_{i,a}$ and $P_{i,c}$

$\mathcal{F}_{(i,\, a+d)}$ …… Etc.

By calculating the function distance ratio for standard functions in the PDFAs, we find

$PDFAs_1(P_{i,a}, P_{i,b}) = 1.704$ $PDFAs_2(P_{i,a}, P_{i,c}) = 6.590$

$PDFAs_3(P_{i,a}, P_{i,d}) = 6.217$ $PDFAs_4(P_{i,b}, P_{i,c}) = 6.675$

$PDFAs_5(P_{i,b}, P_{i,d}) = 5.732$ $PDFAs_6(P_{i,b}, P_{i,d}) = 6.594$

The smallest distance among all car models is between Buick Regal and Buick LaCrosse. Small gap indicates almost no differentiation between the two car models. The function and function attribute value are almost identical. This is very expected when the modularization strategy is used. In contrast, the biggest gap is between Buick LaCrosse and Chevrolet Malibu.

5.1.1.2 Exclusive Platform Differentiation Functions Analysis (PDFAe)

Considering exclusive functions in the PDI for the given P_a P_b, P_c, and P_c, the exclusive functions analysis or every platform and they are :

$PDFAe_1(P_{i,a}, P_{i,b}) = 1$ $PDFAe_2(P_{i,a}, P_{i,c}) = 2$

$PDFAe_3(P_{i,a}, P_{i,d}) = 0$ $PDFAe_4(P_{i,b}, P_{i,c}) = 3$

$PDFAe_5(P_{i,b}, P_{i,d}) = 1$ $PDFAe_6(P_{i,b}, P_{i,d}) = 2$

The differentiation between LaCrosse and Malibu scores the highest number. There are three functions that are offered exclusively between the two models. In contrast, Regal and CTS contain no exclusive functions. any difference between Regal and CTS is mostly in the standard functions and attribute values.

By considering all platforms, standards, exclusive and marketable functions, we now can calculate the Platform Diversification Index (PDI) by apply equation 3.6, $PDI(P_{i,a}, P_{i,b})$ calculates the initial diversification between any two platforms.

$PDI(P_{i,a}, P_{i,b}) = 0.129$ $\quad PDI(P_{i,a}, P_{i,c}) = 0.39$

$PDI(P_{i,a}, P_{i,d}) = 0.311$ $\quad PDI(P_{i,b}, P_{i,c}) = 0.421$

$PDI(P_{i,b}, P_{i,d}) = 0.321$ $\quad PDI(P_{i,b}, P_{i,d}) = 0.391$

The second step is to understand the diversification of any platform in relationship to the rest of the platforms within or between product families. By equation 3.7, given $PDI(P_{i,b})$, we calculate the average of all $PDI(P_{i,b})$ for every $(P_{i,b})$ in the family

$$PDI_{F_i}(P_{i,a}) = \frac{1}{(F_N - 1)} \sum_{P_{i,c,a} \in F_{i,}\ b \neq a, \neq c} PDI(P_{i,b}, P_{i,a}), PDI(P_{i,b}, P_{i,c})$$

$PDI\ (P_a) Buick\ Regal = 0.138$ $\quad PDI(P_b)\ Buick\ LaCross = 0.145$

$PDI(P_c) Caddilac\ CTS = 0.200$ $\quad PDI(P_c) Chevrolet\ Malibu = 0.170$

Vehicle model Chevrolet Malibu has the most efficient power among all four vehicle models. Therefore, the Dominated product Platform (D_p) for an enterprise to maintain with respect to profit and market share can be achieved by:

$$D_{p(P_a)} = \left(\frac{P_a}{\text{Max}\ PE_p}\right) * 100$$

$$D_{p(P_a)}\ Cadillac\ CTS = 21.97\ \%\ Domination$$

$$D_{p(P_b)}\ Buikc\ Regal = 23.03\ \%\ Domination$$

$$D_{p(P_c)}\ Buick\ LaCross = 25.62\ \%\ Domination.$$

$$D_{p(P_d)} Chevrolet\ Malibu = 100\ \%\ Domination.$$

The dominated product model is the strongly recommended model to maintain and develop in the enterprise as it has the highest market share among others. Therefore, Chevrolet Malibu is the most dominated car in the same product platform.

5.1.2 Families Diversification Index (FDI)

In CY 20012, General Motors manufactured four different product families, Buick, Cadillac, Chevrolet and GMC. Production volumes for all four product families along with the associated product platforms for each family is illustrated in table 5.5

	GM Company (2012 Production Volume) – Product Family							
	Buick		Cadillac		Chevrolet		GMC	
Product Platform	**Vehicle**	**Volume**	**Vehicle**	**Volume**	**Vehicle**	**Volume**	**Vehicle**	**Volume**
	Verano	41,042	ATS	10,532	Sonic	72,541	Acadia	78,280
	Regal	26,383	CTS	46,979	Cruze	241,859	Sierra	157,185
	LaCrosse	57,076	XTS	15,049	Volt	13,548	Yukon	27,818
	Encore	60,587	SRX	57,953	Malibu	210,951	Terrain	97,786
	Enclave	57,632	Escalade	22,632	Impala	86,214		
					Camaro	68,245		
					Corvette	42,532		
					Equinox	218,621		
					Traverse	85,606		
					Tahoe	68,904		
					Suburban	48,116		
					Colorado	36,840		
					Avalanche	23,995		
					Silverado	418,312		

Table 5.5: GM - MY2013 Production Volume

The production volume gap between product families, as illustrated in figure 5.3, is very clear as Chevrolet family ranks number 1 among all other families. The required decision is what other family should stay in the market, and what platforms. The mathematical model will analyze the situation and provide recommendations to restructure the product families. The four product families will be analyzed to review functions and attributes in conjunction to the market share.

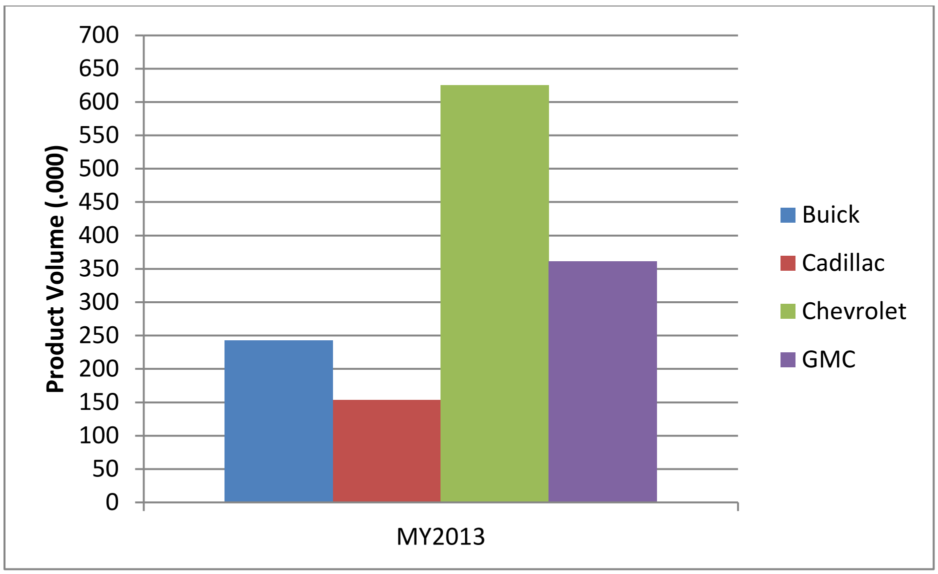

Figure 5.3: GM - MY2013 Production Volume

The given product families F_a, F_b, F_a, and F_c refers to Buick, Cadillac, Chevrolet, and GMC product families consecutively. Functions in all four families are classified for analysis in the following two sections

5.1.2.1 Exclusive Family Differentiation Function Analysis (FDFAe)

In the exclusive function analysis, for each function F_t in every product family, as defined in table 4.3, we calculate family efficiency and deficiency scores for each product family:

The Exclusive Family Efficiency Score (FESe) for Buick family (F_a) is calculated by adding all FESe of (F_a) against Cadillac family (F_b) Chevrolet (F_b), and GMC (F_d):

$$\text{FESe} = \sum_{f_t \in F_{(a-b)}} \frac{R_t^{a-b}}{L_t} + \sum_{f_t \in F_{(a-c)}} \frac{R_t^{a-c}}{L_t} + \sum_{f_t \in F_{(a-d)}} \frac{R_t^{a-d}}{L_t}$$

	Functions	R_t^{a-b}/L_t	R_t^{a-c}/L_t	R_t^{a-d}/L_t
exclusive functions / marketable	Hitch back door	0.33	0.00	0.33
	4 X4 Drive	0.00	0.00	0.00
	Driving Assistant / GPS	0.33	0.00	0.33
	Hybrid Engine	0.00	0.00	0.00
	Electrical Engine	0.00	0.00	0.00
	Heavy duty	0.00	0.00	0.00
	Convertible	0.00	0.00	0.00
	Pick-up w/double cabin-Crew	0.00	0.00	0.00
	Coupe - 2 Doors	0.00	0.00	0.00
	Wagon	0.00	0.00	0.00
	low end class	0.00	0.00	0.00
	High-End Class	0.00	0.36	0.07
	unique Platform segment	0.00	0.00	0.20
	Total	**0.67**	**0.36**	**0.94**

Table 5.6: FESe for Buick Product Family

Therefore:

FESe (F_a) = 1.96 FESe (F_b) = 14.43

FESe (F_c) = 20.83 FESe (F_d) = 1.24

Chevrolet product family is the most efficient family which differentiates itself from other families by offering unique functions that are not available in others. The next efficient family is the Cadillac family.

In contrast, equation 3.9 calculates the Exclusive Family Deficiency Score (FDSe), and the scores are:

$$= -\sum_{f_t \in F_{(b-a)}} \frac{R_t^{b-a}}{L_t} - \sum_{f_t \in F_{(c-a)}} \frac{R_t^{c-a}}{L_t} \sum_{f_t \in F_{(d-a)}} \frac{R_t^{d-a}}{L_t}$$

FESe (F_a) = -8.7 FESe (F_b) = -7.9

FESe (F_c) = -2.0 FESe (F_d) = -9.49

GMC scores the highest number in the deficiency ranking, which means that most of the functions offered by Buick, Cadillac, and Chevrolet, are no offered by GMC. On the other hand, Chevrolet scores only -2.0 deficiencies. There are only limited numbers of functions that Chevrolet does not offer in the fleet.

5.1.2.2 Standard Family Differentiation Function Analysis (FDFAs)

The Standard Family Differentiation Function Analysis (FDFAs) investigates the standard functions in more depth. Functions attributes and their values are analyzed to understand the gap between product families. Substitute values in equation 3.10 to 3.14. We find the FDI for every product family:

Family Diversification Index (FDI) – Buick = 10.02

Family Diversification Index (FDI) – Cadillac = -15.5

Family Diversification Index (FDI) – Chevrolet = 70.05

Family Diversification Index (FDI) – GMC = -20.22

FDI index, without considering production volume, recommends the following:

Chevrolet and Buick families should stay in the market, Cadillac and GMC should be discontinued. However, incorporating the market share into the mathematical model indicates if the functions in every family are desirable for the end users. The family Efficiency Power EP_f and the Dominated Family (D_f) will contribute in the enterprise executive decision.

Substituting variables in equations 3.15 to 3.17, we find:

$D_{f(a)}$ Buick = -2.14 % domination

$D_{f(b)}$ Cadillac = -2.26 % domination

$D_{f(c)}$ Chevrolet = 100 % domination

$D_{f(d)}$ GMC = -7.0 % domination

The domination level indicates the most saleable product family in the market with highest market share. This domination indicates that functions and attributes offered by this family are the most desirable to the end users. Other functions offered by other families can be offers on module bases as needed.

Chevrolet ranks number one, and the analysis recommends maintaining this family in production. Cadillac and Buick rank number two and three respectively with negative value but close to zero.

5.1.3 Family Saturation Index (FSI)

This section will evaluate and assess the Family Saturation Index (FSI) for the available functions and functions attributes in the target family (F_a) but not in other families (F_{N-a}). Each attributer Saturation Scored is calculated from equation 3.18, and the Family Saturation Index (FSI) is calculated from equation 3.19.

By substituting variables in both equations, we find:

Buick Product Family (FSI) = 112.26%

Cadillac Product Family (FSI) = 112.28%

Chevrolet Product Family (FSI) = 175.8%

GMC Product Family (FSI) = 107.07%

A value with more than 100% saturation level indicates that the family offer redundant functions and function attributes. The ultimate saturation level for an enterprise to be healthy is in the range between 90%-100%. Chevrolet family manufactures vehicles with high redundancy, and covers and access all functions offer in the other three families.

5.1.4 Family Unsaturation Index (FUI)

The unsaturation index needs to be calculated to understand what functions and function attributes are available in other families, but not in the evaluated family. For simplicity, let the target family to be (F_a), and (F_{N-a}) as the set of all other product families.

5.1.4.1 Exclusive Function Unsaturation Score (FUSe)

We donate $\mathcal{F}(\ (F_{N-a}) - F_a)$ for functions available in all product families (F_{N-a}) but not in (F_a). Functions available in all product families but not in (F_a), we assign($(F_{N-a}) - F_a$).

The Exclusive Function Unsaturation Score (FUSe) ($F_{N-a}), F_a$ is calculated by:

$$\frac{1}{total_f^{a+(N-a)}} \sum_{f_t \in F_{(N-a)-a}} (R_t^{(N-a)-a})$$

Buick (FUSe) = 84.5% Cadillac (FUSe) = 82.1%

Chevrolet (FUSe) = 47.6% GMC (FUSe) = 85.7%

5.1.4.2 Standard Function Unsaturation Score (FUSs)

A deep dive analysis is conducted on function attributes level for each in the standard functions, and then further analysis is calculated on function level. The Standard Attribute Unsaturation Score (AUSs) is calculated from equation 3.21 and 3.22=

$$\left(f_t, b_l^t, F_a, F_{(N-a)}\right) = \frac{\sum^{T}_{\substack{i=1 \\ \theta_{l,i}^t=0}} \left(\vartheta_{l,i}^t\right)}{\sum_{i=1}^{T}\left(\theta_{l,i}^t - \vartheta_{l,i}^t\right)}$$

Buick (FUSe) = 28.18% Cadillac (FUSe) = 26.5%

Chevrolet (FUSe) = 8.39% GMC (FUSe) = 22.49%

By calculating the both exclusive and standard functions, now we can calculate the entire product Family Unsaturation Index (FUI) by adding both scores and divide by 2, per equation 3.23, which distributes and normalizes the overall family unsaturation.

As a result, the Family Unsaturation Index (FUI) =

$$\frac{1}{2}\left[\frac{1}{total_f^{a+(N-a)}} \sum_{f_t \in F_{(N-a)-a}} \left(R_t^{(N-a)-a}\right) + \frac{1}{\boldsymbol{F_a} + \boldsymbol{F}_{(\boldsymbol{N-a})}} \sum_{f_t \in F_{(a+N-a)}} \frac{1}{T_t} \sum_{t=1}^{T_t} \text{AUSs}\left(f_t, b_l^t, F_a, F_{N-a}\right)\right]$$

Buick (FUSe) = 42.26% Cadillac (FUSe) = 41.07%

Chevrolet (FUSe) = 23.81% GMC (FUSe) = 42.86%

5.2 Analysis validation and recommendations

This section provides an overall executive review of the mathematical model outcomes after analyzing the product platforms and the product families, for all current car models manufactured and offered by the enterprise, General Motors.

Considering all current platforms and product families, The Family Diversification Index analyzes the enterprise families, and we observe that some families carry no significant value to the organization market shares. Per table 5.7, we observe the following:

Family	Family Diversification Index	Family Saturation Index (%)	Family Unsaturation Index (%)	Family Efficiency Power	Dominated product Family
Buick Family against Cadillac, Chevrolet, and GMC families	-10.02	112.26	42.26	-100.6	-2.15
Cadillac Family against Buick, Chevrolet, and GMC families	-15.50	112.28	41.07	-106.28	-2.27
Chevrolet Family against Buick, Cadillac, and GMC families	70.05	175.80	23.81	4684.66	100.00
GMC Family against Buick, Cadillac, and Chevrolet families	-20.22	107.07	42.86	-328.05	-7.00

Table 5.7: GM Evaluation Results for Current Product Families

1. Buick, Cadillac, and GMC are not offer any different functions by any means to comparison to the Chevrolet family
2. All product families are saturated with functions and function-attributes available in other families.
3. Chevrolet family carries all functions available in other family, and 75% repeatability within the same family
4. Considering overall standard and exclusive functions, 23% of functions offered in Buick, Cadillac, and GMC are not offered in Chevrolet

The Platform Diversification Index analyzed all current product platforms within, and across all product families. We observed that some platforms are highly recommended to be eliminated or discontinued from the market as they do not offer any substantial differences in their functions to increase the market shares.

By applying the model recommendations to the enterprise product platforms, and maintain all four different product families as they are listed in table 5.6, the FDI outcomes are illustrated in table 5.9, and the observations are that Cadillac product family has more divers functions and almost close to pass the negative line.

Product Platform	**Product Family**			
	Buick	**Cadillac**	**Chevrolet**	**GMC**
subcompact-Size vehicle			Sonic	
Compact-Size Vehicle	Verano		Cruze & Volt	
Mid-Size Vehicle		CTS	Malibu	
Full-Size Vehicle		XTS	Impala	
compact-Size SUV	Encore			
Mid-Size SUV			Equinox	Terrain
Full-Size SUV		Escalade	Tahoe	
Mid-Size Crossover		SRX		
Full-Size crossover SUV			Traverse	Acadia
Mid-Size pick-up-			Colorado	Sierra
Full-Size Pick-up			Silverado	
Sport Vehicle			Camaro	

Table 5.8: GM - Recommended Product Platform per Product Family

Product Family	**Family Diversification Index**	**Family Saturation Index (%)**	**Family Unsaturation Index (%)**	**Family Efficiency Power**	**Dominated product Family**
Buick Family Vs. Cadillac, Chevrolet, and GMC families	-14.02	110.55	65.97	-67.9	-1.46
Cadillac Family Vs. Buick, Chevrolet, and GMC families	-8.19	113.05	55.62	-55.61	-1.2
Chevrolet Family Vs. Buick, Cadillac, and GMC families	64.16	177.51	26.54	4650.94	100.00
GMC Family Vs. Buick, Cadillac, and Chevrolet families	-16.21	105.39	54.17	-257.37	5.53

Table 5.9: GM Analysis Outcomes – Four Product Families

The mathematical model recommends keeping the Cadillac family, and consolidates all other families under one name. The two families will be classified as low-end and high-end class families as illustrated in table 5.10

Product Platform	Product Family	
	Chevrolet Family (Low-End)	Cadillac Family (High-End)
subcompact-Size vehicle	Sonic	
Compact-Size Vehicle	Cruze & Volt	Verano
Mid-Size Vehicle	Malibu	CTS
Full-Size Vehicle	Impala	XTS
compact-Size SUV		Encore
Mid-Size SUV	Equinox	Terrain
Full-Size SUV	Tahoe	Escalade
Mid-Size Crossover		SRX
Full-Size crossover SUV	Traverse	Acadia
Mid-Size pick-up-	Colorado	Sierra
Full-Size Pick-up	Silverado	
Sport Vehicle	Camaro	

Table 5.10: Recommended Families and Platforms for GM Enterprise

By doing so, the outcomes are shown in table 5.11, and the observations are:

Family	Family Diversification Index	Family Saturation Index (%)	Family Unsaturation Index %	Family Efficiency Power	Dominated product Family
Chevrolet family against Cadillac Family	16.86	147.23	24.95	1222.37	100.00
Cadillac Family against Chevrolet family	13.1	79.85	36.85	85.28	6.98

Table 5.11: GM Analysis Outcomes – Two Product Families

1. Chevrolet family has more diversification than Cadillac family due to the higher number of platforms offered by Chevrolet
2. The recommendation is Keep both families, Cadillac and Chevrolet in production as indicated in the positive diversification index
3. Cadillac family includes 79% of standard functions offered by Chevrolet family, and only 36% deficiency over all of standard and exclusive functions
4. Chevrolet family includes all functions offered in the Cadillac family, and only 24% not offered.
5. Chevrolet family efficiency went down as Cadillac went up to level the efficiency
6. Cadillac family domination increased from -2.27 initially, to positive 6.98

6. CHAPTER SIX - CONCLUSION AND FUTURE WORK

6.1 Summary and Observations

Product platform and product family offered by any enterprise is a way to provide different products to serve and satisfy as many market segments as possible. Covering a wide range of market segment increases the possibility to increase market shares, and potentially revenue. However, products' portfolio with redundant functions creates self-competition. Redundancy is unhealthy, where diversifications in products are essential in the global competitive market.

Chapter one introduced the motivation of the dissertation to eliminate the phenomenon of the self-competition and understand the company position in the global market. In addition, research gap analysis, problem statement, and research objectives were introduced. Chapter two presented and introduced product design and development process, product architecture design models and structure, modularity architectures and measure, and product design and variation approach models. The core of chapter two was 1) introduction to product platforms' design models along with advantages and disadvantage 2) introduction to product families; advantages and design methodologies. Chapter three presented the mathematical model approach for product platforms and families. The classifications and the sequence of the research approached were presented as well. Chapter four demonstrated an actual case study from the automotive industry for Ford Motor Company for calendar year 2006. Outcomes of the research with recommendations matched the current company portfolio for both product platforms and product families. The model was validated and proved its validity. Chapter five studied and evaluated the current portfolio status for General Motors, for calendar year 2013. The model made recommendations and suggestion to implement changes.

The focus of this research is to identify the ultimate number of product platforms and product families of existing and prospective products of an enterprise. The model discovered the top features and functions needed in the market. The process is demonstrated using real industry case studies. It is demonstrate that using the proposed model, the ultimate number of platforms and families can be identifies along with most demanded functions and functions attributes. this identification helps the company to reduce design cost, reduce vehicle validation cost, increase revenue, invest more into technology, and offer distinctive features to the market.

6.2 Conclusion

The automotive industry has changed dramatically in the last twenty years and the world has become more global. Global competition defeated the market domination business model as customers have the opportunities to select products based on quality, price, technology, and reputation.

The following observations and conclusions can be made from the presented research:

1. Product platform are product family play a significant factor in correlation to the market share. However, it might not be the sonly causation.
2. Product platforms have potential to increase market share by attracting new market segments.
3. Enterprises are recommended to use product modularity to meet customer needs and increase revenue. Modularity concept offers rapid response to customer needs and market fluctuations
4. Product variety increased the complexity of planning in general and required well-designed strategies and models to handle it.
5. Product platforms are designed to target different market segments based on customer needs, where product families are designed to target market segments based on income and prestige.
6. The relationship between product functions, market shares, and enterprise product families and platforms is very important and crucial as it has been demonstrated and validated in the proposed mathematical model.

7. Product variations should be initiated and created by increase the number of platforms to serve new potential market segments
8. End-users tend to lead toward product platform to satisfy their day-to-day activities, rather than product family.
9. Redundancy and self-competition should be avoided to achieve a healthy and profitable balance sheet.
10. Multi-car model design in the same family and platform does not increase market share.

6.3 Research Contributions

The research presented in this dissertation contributes to the field of product platforms and families design methodology, and by extension, functions and function attributes identifications. The proposed mathematical model has the possibility to be applied on other industries beside the automotive. The research formulated and developed a mathematical model to quantify and evaluate the current enterprise products and vehicle models on both levels: product platforms and product families. The mathematical approach presented a relationship between product family, product platform, market share percentage with respect to offered features, functions, and function attributes. In addition, the proposed approach provided a comprehensive evaluation of product models within the same platform and family, and then recommended the appropriate number of vehicle models, families, and platforms. Further analysis identified the saturation level of product families to identify missing functions. Finally, the proposed mathematical model evaluated and identified the efficiency and deficiency of available product families, product platforms, and product car models.

6.4 Future Work

Recommendations are made to eliminate the enterprise self-competition by reducing product platforms and product families without reducing market shares. Many questions and issues which were raised and in the course of research; Majority of the issues were addressed in the dissertation systematically. The remaining concerns can be lead to future research topic.

1. One of the most important future contributions can be made in the field of the automotive industry is the overall vehicle design geometry and appearance. Potentially, customers tend to be attracted toward prestige and sophisticated design geometry more than the functionality of the vehicle. To fulfill customer expectations toward design appearance, a further research should be conducted to identify the vehicle life-time before unveiling new design shape.

2. Conduct a longitudinal study to report conclusion of the same variable over longer period of time.

3. Another area of promising future research is vehicle retail price. Majority of end-users, especially entry level or low-end vehicle segments, tend to purchase an automobile based on the pricing. Correlate functions and functions attributes to vehicle price might be essential to determine market shares.

4. Another important point to be researched in the future is the relationship between market shares, marketing, advertisement, and promotional incentives. Of course, incentives might reduce the profit margin. However, the enterprise has to prioritize and identify the tradeoffs between market share and profit margin.

5. One of the limitations of this research is the customer perception toward brand and product quality. In future research, these can be treated as uncertain factors which influence market shares stability and profitability. How does product quality in product platform and families add values potential buyers? What would happen if a prestige company like BMW suffered for a massive recall toward safety? What is the quality impact on market shares and in highly competitive global market which will influence and potentially change customer perception?

6. The researched considered only vehicles sold in the North American market. Future research has the opportunity to consider the market share of an enterprise on a global scale. Of course global research requires many areas to be instigated including, region population, average house-hole income, culture, perception toward foreign products, and global inflation.

7. Finally, strategically locate manufacturing facilities based on highest market share volume for the enterprise to reduce supply chain management, product logistics complexity, minimize resources and cost, be more responsive to customer demand, and adopt cultural behavior,

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8. APPENDIXES

APPENDIX A

Product Platform Variation

(Courtesy of Chrysler)

APPENDIX B-1
Function attributes survey - Seat Headroom

11:00 #3

UF Front and Rear Seat Headroom

Name: ______________ Gender: Male / Female

Age Group: Under 19 20-25 26-35 36-45 46-55 56-Older

Height: ______

Current Vehicle: Make:______ Model: ______ MY: ______

How often do you transport passengers in the rear seat? Never Sometimes Often All the time

Check all that apply

What are the ages of the passengers in the rear seat? ☐ Children (< 18 yrs.) ☐ Adults (=> 18 yrs.)

Thank you for helping us with this important research. Today you will be evaluating five vehicles on various front and rear seat characteristics.

Note: Opening/closing of the UF buck (G4) doors requires special handling; not to be done by participant

Instruct participant to get into the driver seat and close the door. Once seated, instruct participant to adjust the seat as if you are going to drive the vehicle.

Vehicle

1 How would you rate the overall roominess of the driver seat area? *(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")*

T4	G4	Q4

2 How would you rate the leg room of the driver seat area? *(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")*

T4	G4	Q4

3 How would you rate the head room of the driver seat area? *(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")*

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

4 How would you rate the shoulder room of the driver seat area? *(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")*

T4	G4	Q4

Turn Page Over

UF Front and Rear Seat Headroom

10 **How would you rate the shoulder room of the rear seat area?** *(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")*

T4	G4	Q4

11 **How would you rate the forward visibility from the rear seat area?** *(on a scale from 1 to 10 with 1 meaning "Poor" and 10 meaning "Excellent")*

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

12 **How would you rate the side visibility from the rear seat area?** *(on a scale from 1 to 10 with 1 meaning "Poor" and 10 meaning "Excellent")*

T4	G4	Q4

13 **How would you rate the ease of getting in and out of the rear seat?** *(on a scale from 1 to 10 with 1 meaning "Not at All Easy" and 10 meaning "Extremely Easy")*

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

TO BE COMPLETED AFTER ALL VEHICLES HAVE BEEN EVALUATED

14 **How important is** ***roominess of the front seat area*** **in your purchase decision?** *(on a scale from 1 to 10 with 1 meaning "Not at All Important" and 10 meaning "Extremely Important")*

Please explain ______

15 **How important is** ***roominess of the rear seat area*** **in your purchase decision?** *(on a scale from 1 to 10 with 1 meaning "Not at All Important" and 10 meaning "Extremely Important")*

Please explain ______

16 **Would you** ***trade off roominess for a sportier appearance*** **when purchasing a vehicle?** Y | N

Please explain ______

UF Front and Rear Seat Headroom

Vehicle

5 How would you rate the visibility to the rear from the driver seat area? ***(on a scale from 1 to 10 with 1 meaning "Poor" and 10 meaning "Excellent")***

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

6 How would you rate the ease of getting in and out of the driver seat area? ***(on a scale from 1 to 10 with 1 meaning "Not at All Easy" and 10 meaning "Extremely Easy")***

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

Note: Opening/closing of the UF buck (G4) doors requires special handling; not to be done by participant

Instruct participant to get into the REAR SEAT on the PASSENGER SIDE of the vehicle and close the door.

7 How would you rate the overall roominess of the rear seat? ***(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")***

T4	G4	Q4

8 How would you rate the leg room of the rear seat area? ***(on a scale from 1 to 10 with 1 meaning "Not at all Roomy" and 10 meaning "Extremely Roomy")***

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

9 How would you rate the head room of the rear seat area? ***(on a scale from 1 to 10 with 1 meaning "Not at All Roomy" and 10 meaning "Extremely Roomy")***

T4	G4	Q4

Observations/comments:

T4 ______

G4 ______

Q4 ______

(Courtesy of Chrysler)

APPENDIX B-2
Function attributes survey – 2nd row Ingress/Egress/Visibility

Gender: Male Female   Shoe Size: Shoes with heels? Yes No

Height: <=5'1" 5'2"-5'6" 5'7"-6'0" >=6'1"   Weight: <=109 110-139 140-169 170-199 200-229 >=230

***Please rate the following on a scale of 1-10. Please refer to table on second page.

2nd Row SEAT - INGRESS/EGRESS   VEHICLES

Please enter and exit the vehicle.	A	B	C	D	E	COMMENTS
Ability to enter the seat	Driver Side Pass Side	Pass Side	Pass Side	Pass Side	Pass Side	A B C D E
Ability to exit the seat	Driver Side Pass Side	Pass Side	Pass Side	Pass Side	Pass Side	A B C D E

3rd Row SEAT - INGRESS/EGRESS   VEHICLES

Please enter and exit the vehicle.	A	B	C	D	E	COMMENTS
Ability to enter the seat	Driver Side Pass Side	Pass Side	Pass Side	Pass Side	Pass Side	A B C D E
Ability to exit the seat	Driver Side Pass Side	Pass Side	Pass Side	Pass Side	Pass Side	A B C D E

1st Row SEAT - Visibility   VEHICLES

Please sit in the driver's seat and look over your right & left shoulders as if switching lanes. Please rate outward/downward visibility	A	B	C	D	E	COMMENTS
Driver's Seat Visibility	Driver Seat	Driver Seat	Driver Seat	Driver Seat	Driver Seat	A B C D E

2nd Row SEAT - Visibility   VEHICLES

Please sit in the second row and rate your outward/downward visibility	A	B	C	D	E	COMMENTS
2nd Row Visibility	Driver Side Pass Side Pass Side+	Pass Side	Pass Side	Pass Side	Pass Side	A B C D E

RATING SCALE	CONDITION DESCRIPTION	FEATURE DESCRIPTION	CUSTOMER REACTION
10	Subjectively undetectable	Perfect	- -
9	Trained observer must be tuned in & looking for condition	Excellent	- -
8	Condition detected by only the most perceptive customer	Very Good	Delighted
7	Customer seldom aware of condition	Good	Satisfied
6	Customer frequently aware of condition, but doesn't consider it a problem	Fair	Aware
5	Condition less than desirable or competitive, and borders on annoying	Borderline	Disappointed
4	Condition annoying and correction desired	Poor	Annoyed
3	Condition unacceptable and must be fixed	Terrible	Angry
2	Intolerable to all customers	Ridiculous	- -
1	Painful or destructive	Impossible	- -

(Courtesy of Chrysler)

APPENDIX C
Automotive vehicles offered in North American market and globally.

North American Automotive Vehicles		
Enterprise	**Ownership**	**Markets**
Toyota Motor Corporation (Japan)		
Lexus	Division	Global
Scion	Division	North America
Toyota	Division	Global
General Motors Company (United States)		
Buick	Division	North America, Middle East, East Asia
Cadillac	Division	Global
Chevrolet	Division	Global
Olds Mobile	Division	Global
Hummer	Division	Global
Pontiac	Division	North America
GEO	Division	North America
Saturn	Division	Global
GMC	Division	North America, Middle East
Opel	Division	Global, except NA.
Volkswagen Group AG (Germany)		
Volkswagen	Subsidiary	Global
Audi	Subsidiary	Global
SEAT	Subsidiary	Europe, South America, North Africa, Middle East
Skoda	Subsidiary	Global, except North America and South Africa
Bentley	Subsidiary	Global
Ford Motor Company (United States)		
Ford	Division	Global
Lincoln	Division	North America, Middle East, South Korea, Japan
Jaguar	Division	Global
Volvo	Division	Global
Land Rover	Division	Global
Mazda	Division	Global
Mercury	Division	North America, Middle East
Honda Motor Company (Japan)		
Acura	Division	North America, East Asia, Russia
Honda	Division	Global
Nissan Motor Company (Japan)		
Infiniti	Division	Global, except South America and Africa
Nissan	Division	Global
Mercedes (Germany)		

Maybach	Division	Global
Mercedes-Benz	Division	Global
Smart	Division	North America, Europe, South East Asia, South Africa
BMW AG (Germany)		
BMW	Division	Global
MINI	Division	Global
Mazda Motor Corporation (Japan)		
Mazda	Division	Global
Chrysler Group, LLC (United States)		
Chrysler	Division	Global
Dodge	Division	Global
Eagle	Division	North America
Jeep	Division	Global
Plymouth	Division	North America
Mitsubishi Motors Corporation (Japan)		
Mitsubishi	Division	Global

APPENDIX D
Chrysler Families and Platforms

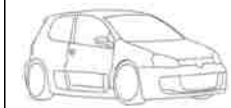
Alfa 4C	
Alfa Spider	
Fiat 500L	
Dodge - Sedan	
Jeep SUV	
Ram 3500	
Ram 3500	
Ram 2500	

Dodge Journey	
SUV	
Fiat Freemont	
Jeep Wrangler 2-Dr	
Jeep Wrangler 4-Dr	
200 Convertible	
Chrysler 200	
Dodge Avenger	

Dodge Charger	
Chrysler 300	
Jeep Compass	
Jeep Patriot	
Jeep C-SUV	
Dakota	
Alfa C-Sedan	
Dodge Dart	

Ram 4500/5500	
Ram 1500	
Ram 1500	
Fiat SUV	
Fiat 500	
Ram Doblo	
Dodge Durango	
SRT Viper	

Dodge Nitro	
Jeep Liberty	
Cherokee	
Dodge LC MCA	
Dodge Challenger	
Jeep Grand Cherokee	
Maserati SUV	
Jeep Grand Wagoneer	

Chrysler C-Hatchback	
Dodge Caliber	
Chrysler MUV	
Minivan - VW	
Minivan	
Minivan	
Segment Sedan	
Ram Ducato	

APPENDIX E
BMW Product Platform and Product Family History

APPENDIX F
Mercedes-Benz Product Platform and Product Family History

APPENDIX G
U.S. Total Vehicle Sales Market Shares - by Company, 1970-2011

Enterprise	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992
BMW	2.3	2.3	2.3	2.3	2.0	1.8	1.8	1.7	1.6	1.5	1.2	1.1	0.9	0.8	0.8	0.7	0.6	0.6	0.6	0.5
Chrysler	10.5	9.2	8.8	10.8	12.6	12.6	13.2	12.8	12.5	12.9	13.0	14.2	15.2	15.7	14.9	15.9	14.3	14.3	14.4	13.1
Daimler	2.7	2.5	2.4	2.4	2.1	2.4	2.2	2.0	1.9	1.8	1.8	1.9	2.0	1.8	1.3	1.1	1.0	0.9	0.8	0.7
Ford	16.5	16.4	15.3	14.2	14.6	16.0	17.0	18.0	19.2	19.9	21.6	22.6	23.2	24.4	24.9	25.2	25.5	25.1	25.4	24.7
GM	19.2	18.8	19.6	21.9	23.2	23.9	25.6	26.9	27.7	28.3	28.0	28.0	28.8	28.7	30.6	30.8	32.2	32.7	33.1	33.7
Honda	8.8	10.5	10.9	10.6	9.4	8.9	8.4	8.1	8.0	7.3	6.9	6.5	6.2	6.3	6.1	5.5	5.3	5.1	5.1	5.9
Hyundai	5.0	4.6	4.1	3.0	2.8	2.7	2.6	2.4	2.4	2.2	2.0	1.4	0.9	0.6	0.7	0.7	0.7	0.8	0.8	0.8
Int.	0.6	0.5	0.5	0.5	0.4	0.7	0.6	0.5	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Isuzu	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9
Jaguar	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Kia	3.7	3.0	2.8	2.0	1.9	1.7	1.6	1.6	1.4	1.4	1.3	0.9	0.8	0.5	0.4	0.2	0.2	0.1	0.0	0.0
Land Rover	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.0	0.0
Mazda	1.9	2.0	2.0	2.0	1.8	1.6	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.5	1.4	1.5	1.9	2.4	2.4	2.6
Mitsubishi	0.6	0.5	0.5	0.7	0.8	0.7	0.7	0.9	1.5	2.0	1.9	1.8	1.5	1.2	1.2	1.2	1.3	1.5	1.3	1.4
Nissan	8.0	7.7	7.3	7.1	6.5	6.0	6.2	5.7	4.7	4.3	4.0	4.2	3.9	3.9	4.7	4.9	5.1	5.0	4.9	4.5
PACCAR	0.4	0.3	0.3	0.3	0.3	0.5	0.4	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2
Porsche	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Saab	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Subaru	2.1	2.2	2.0	1.4	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.0	0.9	0.9	0.9	0.8	0.7	0.7	0.7	0.8
Suzuki	0.2	0.2	0.4	0.6	0.6	0.6	0.5	0.4	0.3	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Toyota	12.7	15.0	16.7	16.5	16.0	15.0	13.0	11.9	11.0	10.3	10.0	9.1	8.5	8.5	7.9	7.5	7.2	7.1	7.3	7.9
Volkswagen	3.4	3.0	2.8	2.3	2.0	1.9	1.8	1.9	2.3	2.5	2.5	2.5	2.2	1.7	1.1	1.1	0.9	0.7	0.4	0.7
Volvo	0.5	0.5	0.6	0.5	0.7	0.7	0.7	0.8	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Volvo Truck	0.3	0.2	0.2	0.2	0.2	0.4	0.3	0.3	0.2	0.2	0.2	0.3	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.2
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Enterprise	**91**	**90**	**89**	**88**	**87**	**86**	**85**	**84**	**83**	**82**	**81**	**80**	**79**	**78**	**77**	**76**	**75**	**74**	**73**	**72**	**71**	**70**
BMW	0.4	0.5	0.4	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.1
Chrysler	12.0	12.0	13.5	14.0	12.3	11.7	11.8	11.1	9.9	9.9	9.5	9.1	11.1	12.3	13.0	14.4	12.9	14.2	13.5	13.9	13.1	14.9
Daimler	0.7	0.8	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.5	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3
Ford	23.2	23.8	24.5	24.2	23.1	21.2	21.3	21.7	20.8	20.3	19.8	20.5	23.8	26.1	25.8	24.6	25.4	27.4	26.4	26.8	25.5	28.3
GM	34.6	35.2	34.7	35.2	34.7	38.5	40.4	41.7	43.1	43.2	42.9	44.2	44.7	45.9	44.8	46.5	43.1	41.2	43.6	42.9	44.3	38.9
Honda	6.4	6.0	5.3	4.9	4.9	4.3	3.5	3.5	3.3	3.5	3.4	3.3	2.5	1.8	1.5	1.1	0.9	0.4	0.3	0.2	0.1	0.0
Hyundai	0.9	1.0	1.2	1.7	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Int.	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.5	0.7	0.7	0.9	0.8	0.8	0.8	1.1	1.4	1.4	1.4	1.3	1.4
Isuzu	0.9	0.9	0.9	0.8	0.9	0.8	0.7	0.4	0.4	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jaguar	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Land Rover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mazda	2.7	2.5	2.3	2.2	2.2	2.3	2.1	2.0	2.0	1.9	1.7	1.5	1.2	0.5	0.4	0.3	0.7	0.6	0.8	0.4	0.2	0.0
Mitsubishi	1.5	1.4	1.0	0.7	0.8	0.5	0.5	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nissan	4.6	4.4	4.5	4.1	4.9	4.7	5.3	4.8	5.4	5.5	5.4	5.5	4.1	2.8	3.3	2.6	3.0	2.2	2.2	1.9	2.1	1.5
PACCAR	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.2	0.1	0.1	0.1	0.1
Porsche	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1
Saab	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Subaru	0.8	0.8	0.9	1.0	1.2	1.1	1.1	1.1	1.3	1.4	1.4	1.1	0.9	0.7	0.5	0.4	0.4	0.2	0.3	0.2	0.1	0.1
Suzuki	0.2	0.1	0.2	0.4	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Toyota	8.2	7.6	6.5	6.0	6.2	6.3	6.0	5.7	5.9	6.4	6.6	6.2	4.5	3.5	3.9	3.0	3.0	2.3	2.3	2.3	2.5	2.0
Volkswagen	0.9	1.1	1.0	1.2	1.5	1.7	1.9	1.7	1.8	2.1	3.1	3.0	2.4	1.8	2.0	1.8	2.9	3.4	3.6	3.8	4.4	5.6
Volvo	0.5	0.6	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.5	0.4	0.3	0.3	0.3	0.5	0.5	0.4	0.4	0.4	0.4
Volvo Truck	0.2	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.9	1.1	0.9
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

(Source: WardsAuto-Data Center)

APPENDIX H
Product Platform Functions and Function Attributes clustering – Case Study-
Ford Motor Company

	Function	Function Attribute	Ford Fusion Product 1 (My 2006)	Mercury Milan Product 2 (My2006)	Mercury Sable Product 3 (My2006)
Standard Function	Seating	Power driver & passenger seat = 1 passenger only =0	1	1	1
Standard Function	Seating	Back seat: yes=1, no=0	1	1	1
Standard Function	Seating	Front seat type: bucket =1, split bench = 2	1	1	2
Standard Function	Seating	# of passengers	5	5	6
Standard Function	Seating	Front driver seat direction controls / ways	6	6	4
Standard Function	Seating	Front passenger seat direction controls / ways	4	4	4
Standard Function	Seating	Lumbar support driver & passenger: 2, driver: 1, no: 0	0	1	1
Standard Function	Seating	Front armrests: center console: 1 center console flip: 2, flip: 3	1	1	2
Standard Function	Seating	Front head restraints: Adjustable=2, fixed= 1, no= 0	2	2	2
Standard Function	Seating	Rear head restraints : yes w/ action=2 yes & fixed =1, no=0	1	1	0
Standard Function	Seating	Rear seat split: yes= 1, no= 0	1	1	1
Standard Function	Seating	Rear armrest: yes= 1, no= 0	1	1	0
Standard Function	Seating	Seat trim: leather= 1, cloth= 2	2	2	2
Standard Function	Occupant comfort	Front legroom	42.3	42.3	42.2
Standard Function	Occupant comfort	Rear legroom	37	37	38.9
Standard Function	Occupant comfort	Front headroom	38.7	38.7	39.8
Standard Function	Occupant comfort	Rear headroom	37.8	37.8	36.7
Standard Function	Occupant comfort	Front hip room	54	54	54.5
Standard Function	Occupant comfort	Rear hip room	53.4	53.6	55.7
Standard Function	Occupant comfort	Front shoulder room	57.4	57.4	57.3
Standard Function	Occupant comfort	Rear shoulder room	56.5	55.6	56.6
Standard Function	Occupant comfort	Passenger volume	100	100	102
Standard Function	Entertainment	Radio: yes=1, no=0	1	1	1
Standard Function	Entertainment	Cassette player :yes=1, no=0	0	0	1
Standard Function	Entertainment	Cd player: yes=1, no=0	1	1	1
Standard Function	Entertainment	Cd changer compatible: yes=1, no=0	0	0	1
Standard Function	Entertainment	Mp3 capability: yes=1, no=0	1	1	0
Standard Function	Entertainment	Steering wheel audio controls yes=1, no=0	0	1	0
Standard Function	Entertainment	Speakers	4	6	4
Standard Function	Entertainment	Amplifier: yes=1, no=0	0	1	1
Standard Function	Entertainment	Speed-sensitive volume: Yes=1, no=0	1	1	0
Standard Function	Safety	Airbags, frontal driver & passenger = 1, driver only = 0	1	1	1
Standard Function	Safety	Airbags, side impact: yes=1, no=0	1	1	1
Standard Function	Safety	Airbags, side curtain: yes=1, no=0	1	1	0
Standard Function	Safety	Occupancy sensor: yes=1, no=0	1	1	0

	Traction control: yes=1, no=0	0	0	1
	Height adjustable seatbelts front =1, back = 0	1	1	1
	Seatbelt pre-tensioners: Front =1, back = 0	1	1	1
	Daytime running lights: yes=1, no=0	1	1	1
Security	Remote keyless entry: yes=1, no=0	1	1	1
	Panic alarm: yes=1, no=0	1	1	1
	Rear child safety door locks yes=1, no=0	1	1	1
	Content theft deterrent alarm system yes=1, no=0	1	1	0
	Ignition disable: yes=1, no=0	1	1	1
Ventilation	Air conditioning, front: auto:1, manual =0	0	0	0
	Air filter	0	0	1
	Under seat ducts: yes=1,no = 0	1	1	1
	Air conditioning: yes=1, no = 0	1	1	1
Exterior dims.	Length. In.	190.2	191.4	199.8
	Height. In	57.2	55.8	55.5
	Width. In	72.2	72.2	73
Engine	Size	2.3	2.3	3
	Gas = 1, hybrid = 0	1	1	1
	# of cylinder	4	4	6
	Horsepower	160	160	153
	Torque	156	156	186
Auto trans.	Auto - speed	0	0	4
	Manual - # of gears	5	5	0
Breaking system	4 wheel disc: yes=1, no=0	1	1	0
	2 disk / 2 drum: yes=1, no=0	0	0	1
Slide breaking	Anti-lock braking system (abs) yes = 1, no = 0	1	1	1
Drive type	Front wheel = 1, rear wheel = 0	1	1	1
Power mechanism	Front windows: yes = 1, no= 0	1	1	1
	Rear windows: yes = 1, no= 0	1	1	1
	Door locks: yes = 1, no= 0	1	1	1
	1-touch window down: yes = 1, no= 0	1	1	1
Acceleration	0-60 - second	8.3	8.2	8
	1/4 mile time - second	16.6	16.5	16
	1/4 mile speed - mph	84	84	80
	Lateral acceleration (g)	0.8	0.8	0.8
	Slalom speed - mph	60	60	60
Handling	Wheelbase - in	107.4	107.4	108.5
	Front track- in	61.6	61.1	61.6
	Rear track - in	61.3	61.3	62.1
	Turning radius - in	19.4 ''	19.4 ''	19.8 ''
	Drag coefficient	0.33	0.33	0.31
Fuel econ-omy	city mpg	23	23	20
	highway mpg	31	31	27
	weight - lb.	3,151	3,117	3,308
	Fuel tank - gal	17.5	17.5	18
Rear luggage	Volume - cu. Ft	15.8	15.8	16
Tire	Radius, in	16	16	16
Access to	Doors	4	4	4

	vehicle				

Exclusive feature	Towing	Towing weight	0	0	1,250
		Towing charger/switch: yes = 1, no=0	0	0	1
	Sky view - sunroof	Yes = 1, no = 0	0	1	0

APPENDIX I – A
Product Family Standard Functions and Function Attributes – Case Study #1
Ford Motor Company

		Family B - Ford Product Family										
Functions	Function attribute	Compact Size Pick-up - Ranger	Compact SUV Escape	Compact-Size Vehicle Focus	Full-size Van Freestar	Full-size Pick-up - F Truck	Full-Size SUV Expedition	Full-Size Vehicle Taurus	Sport - Thunderbird	Mid-Size SUV Explorer	Mid-Size Vehicle Fusion	Sport Vehicle Mustang
Seating	Power Driver & Passenger seat = 2 Driver Only =1	1	2	1	1	2	1	1	2	2	2	2
	Number of seating rows	1	2	2	3	2	3	2	2	2	2	2
	Back Seat: Yes=1, No=0	0	1	1	1	0	1	1	0	1	1	1
	front seat type: Bucket =1, Split Bench = 2	2	1	1	1	2	2	1	1	1	1	1
	# of passengers	3	5	5	7	6	9	5	2	5	5	4
	front driver seat direction controls / Ways	2	4	6	6	4	6	6	6	4	6	6
	front passenger seat direction controls/ways	2	4	4	4	4	4	4	2	4	4	4
	lumbar support Driver & Passenger= 2, Driver= 1, No= 0	0	0	0	1	2	2	1	1	1	1	1
	Front armrests center console flip: 3 center console =2, armrest=1, No=0	3	3	2	1	3	2	2	2	2	2	2
	Front head restraints Yes Adjustable= 2, Yes Fixed= 1, No= 0	1	2	2	2	1	1	2	2	2	2	2
	rear head restraints Yes w/ action = 2, Yes & Fixed =1, No=0	0	2	0	2	2	2	0	0	2	1	1
	Rear seat split: Yes= 1, No= 0	0	1	1	1	1	1	1	0	1	1	1
	Rear armrest: Yes= 1, No= 0	0	0	0	1	0	1	1	0	0	1	0
	Seat trim: Leather=3, Vinyl=2, cloth= 1	2	1	1	1	1	1	1	3	1	1	1
	Heated Seat: Driver & Pass= 2, Driver = 1, No=0	0	0	0	0	0	0	0	0	0	2	0

Occupant Comfort	Front legroom	42.4	41.6	40.7	40.7	41.3	41.2	42.2	42.7	42.4	42.3	42.7
	Rear legroom	0	35.6	37.6	38	39	38.7	38.9	0	36.9	37	30.3
	Third row legroom	0	0	0	34.1	0	36.3	0	0	0	0	0
	Front headroom	39.3	40.4	39.1	38.9	40.1	39.7	40	37.2	39.8	38.7	38.6
	Rear headroom	0	39.2	38.4	40.1	39.6	39.8	38.1	0	38.9	37.8	34.7
	third row headroom	0	0	0	38.2	0	38.2	0	0	0	0	0
	Front hip room	52.7	53.4	49.4	56.5	63.8	63	54.5	53.7	55.4	54	53.6
	Rear hip room	0	49.1	50.7	66.4	63.8	62.4	55.7	0	55.5	53.4	46.8
	Third row hip room	0	0	0	48.1	0	54.5	0	0	0	0	0
	Front shoulder room	54.5	56.3	53.5	61	65.8	63.4	57.3	57.3	59	57.4	55.4
	Rear shoulder room	0	55.9	53.6	63.5	65.8	64.3	56.6	0	59	56.5	53.4
	Third row shoulder room	0	0	0	50.9	0	60.1	0	0	0	0	0
	Passenger volume cu. Ft	52	99	94	125	65	130	104	53	151	100	85
Entertainment	Radio: Yes:1, No:0	1	1	1	1	1	1	1	1	1	1	1
	Cassette player: Yes:1, No:0	0	0	0	0	0	1	0	0	0	0	0
	CD player: Yes:1, No:0	1	1	1	1	1	1	1	1	1	1	1
	CD Changer: Yes:1, No:0	0	0	0	0	0	0	1	0	0	1	1
	MP3 capability: Yes:1, No:0	0	0	1	0	0	1	0	0	1	1	1
	Rear seat audio control: Yes:1, No:0	0	0	0	0	0	0	0	0	0	0	0
	# of Speakers	2	4	4	4	4	4	4	8	4	6	8
	Speed-Sensitive Volume Yes:1, No: 0	0	0	1	0	1	1	0	1	1	1	1
	entertainment system: Yes=1, No=0	0	0	0	1	0	0	0	0	0	0	0
	1st row LCD screen: Yes=1, No=0	0	0	0	1	0	0	0	0	0	0	0
Safety	airbags, frontal Driver & Passenger = 1 Driver only = 0	1	1	1	1	1	1	1	1	1	1	1
	airbags, side impact – Curtain: yes = 1, No=0	0	1	0	1	0	0	1	1	0	1	0
	occupancy sensor: Front & rear=2, Front= 1 no= 0	0	1	1	1	0	0	1	0	1	1	1
	height adjustable seatbelts : Front & rear =1, front = 0	0	1	0	1	0	1	0	0	0	0	0
	Headlights: Halogen = 1, incandescent = 0	1	1	1	1	1	1	1	1	1	1	1
	Exterior light control Auto =2, Manual =1, No = 0	0	0	0	2	1	2	2	2	2	2	0
	delay-off headlamps: Yes=1, No=0	0	0	0	0	1	1	0	1	0	0	0
	daytime running	0	0	0	0	0	0	0	0	0	0	0

	lights: Yes=1, No=0											
	door curb lights: Yes=1,No=0	0	0	0	0	1	0	0	0	0	0	0
	Illuminated entry: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1	1
	parking assist: Yes=1, No=0	0	0	0	0	0	0	0	0	0	0	0
Security	remote keyless entry: Yes=1, No=0	0	1	1	1	1	1	1	1	1	1	1
	Panic alarm: Yes=1, No=0	0	1	1	1	1	1	1	1	1	1	1
	Door locks: Power = 1, manual= 0	0	1	1	1	1	1	1	1	1	1	1
	rear child safety door locks: Yes=1, No=0	0	1	1	1	0	1	1	0	1	1	0
	content theft deterrent alarm system: Yes=1, No=0	0	0	0	0	0	0	1	1	0	0	0
	ignition disable: Yes=1, No=0	0	1	1	1	1	1	1	1	1	1	1
Ventilation	air conditioning, front Auto:1: Manual =0	0	0	0	0	0	0	0	1	0	1	0
	Air filter: Yes = 1, no=0	0	0	0	1	0	0	1	1	0	0	1
	Under seat ducts: Yes=1, No = 0	0	1	0	1	0	1	1	0	0	1	0
	Air conditioning rear: Yes=1, No = 0	0	0	0	1	0	0	0	0	0	0	0
Exterior Dimensions	Length. In.	200.5	174.9	175.2	201	211.2	205.8	197.6	186.3	193.4	190.2	187.6
	Width In	69.4	70.1	66.7	76.4	78.9	78.7	73	72	73.7	72.2	73.9
	Height In	66.2	69.7	56.8	70.6	73.5	76.6	56.1	52.1	72.8	57.2	54.5
	Exterior Box length	84.6	0	0	0	78	0	0	0	0	0	0
Engine	Size	2.3	2.3	2	4.2	4.2	5.4	3	3.9	4	2.3	4
	Hybrid = 2, Gas = 1	1	1	1	1	1	1	1	1	1	1	1
	# of Cylinder	4	4	4	6	6	8	6	8	6	4	6
	Horsepower	143	153	136	201	202	300	153	280	215	160	210
	torque	154	152	136	263	260	365	186	286	254	156	240
Fuel Economy	city mpg	24	19	26	17	15	14	20	18	15	23	19
	highway mpg	29	22	34	23	20	17	27	24	20	31	28
	weight - Lb.	3028	4420	2685	4301	4758	5607	3322	3775	4615	3151	3351
	fuel tank - gal	20	16.5	14	26	26	28	18	18	22.5	17.5	16
Trans.	Auto=1, Manual=0	0	4	5	4	0	4	4	5	1	1	1
	# of gears	5	0	0	0	5	0	0	0	5	5	5
Braking	4 wheel disc: yes=1, No=0	0	0	0	1	1	1	0	1	1	1	1

	2 disk / 2 Drum: yes=1, No=0	1	1	1	0	0	0	1	0	0	0	0
slide breaking	anti-lock braking system (ABS): yes = 1, no = 0	1	1	1	1	0	1	1	1	1	1	1
Drive Type	Four wheel = 2, Front = 1, Rear = 0	0	2	1	1	0	2	1	0	2	2	2
Power mechanism	Front windows: Auto= 1, manual = 0	0	1	1	1	1	1	1	1	1	1	1
	Rear windows: Auto= 1 manual = 0	0	1	1	0	0	1	1	0	1	1	1
	door locks: Auto= 1, manual = 0	0	1	1	1	1	1	1	1	1	1	1
	1-touch window down: Yes = 1, No= 0	0	1	0	1	1	1	1	1	0	0	1
Acceleration	0-60 - Second	9.6	7.9	8.8	9.4	9.9	8.1	9.6	6.5	8.5	8.3	7
	1/4 mile time - Second	17	16.6	16.5	17.1	17.6	15.9	17.2	15.1	16.5	16.6	15.4
	1/4 mile speed - mph	85	81	85	83	83	83	79	93	79	84	94
	lateral acceleration (g)	0.8	0.8	0.8	0.8	0.7	0.7	0.8	0.9	0.7	0.8	0.8
	slalom speed - mph	59	58	61	58	54	53	60	61	56	60	59
Handling	Wheelbase - In	117.5	103.1	102.9	120.8	126	119	108.5	107.2	113.7	107.4	107.1
	Front track- in	58.6	61.3	58.9	64.3	67	66.9	61.6	60.5	60.9	61.6	62.8
	Rear track - in	57.3	60.9	58.7	63	67	67	62.1	60.2	61.8	61.3	63
	Turning radius - in	19.9	17.7	17.1	19.8	20.9	19.6	19.8	17.6	18.4	20	18
luggage volume	Min volume - cu. Ft	0	29.3	14.8	25.8	0	20.7	17	6.9	45.1	45.8	13.1
	Max volume - cu. Ft	15.2	66.3	14.8	134.3	17.2	110.5	17	6.9	85.8	15.8	13.1
Tire	Radius, in	15	15	15	16	17	17	16	17	16	17	16
Access to vehicle	# of Doors	2	4	4	4	2	4	4	2	4	4	2
pickup box	Length	16.5	0	0	0	22.3	0	0	0	0	0	0
	Width	40.4	0	0	0	50	0	0	0	0	0	0

Functions	Function attribute	Family B - Lincoln Product Family						Family C - Jaguar Product Family			
		Mid-Size vehicle MKZ	Full-Size SUV Navigator	Mid-Size crossover MKX	Mid-size vehicle LS	Full-size pick-up Mark LT	Full-size vehicle Town car	Compact-Size Vehicle - X Type	Full-Size Vehicle XJ	executive S Type	Sport Vehicle XK
Seating	Power Driver & Passenger seat = 2 Driver Only =1	2	2	2	2	2	2	2	2	2	2
	Number of seating rows	2	3	2	2	2	2	2	2	2	2
	Back Seat: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1
	front seat type: Bucket =1, Split Bench = 2	1	1	1	1	1	2	1	1	1	1
	# of passengers	5	7	5	5	5	6	5	5	5	4
	front driver seat direction controls / Ways	8	8	8	8	6	8	8	8	8	8
	front passenger seat direction controls/ways	8	8	8	6	6	8	2	8	6	8
	lumbar support Driver & Passenger= 2, Driver= 1, No= 0	2	2	1	2	2	2	2	2	2	2
	Front armrests center console flip: 3 center console =2, armrest=1, No=0	2	2	2	2	2	3	2	2	2	2
	Front head restraints Yes Adjustable= 2, Yes Fixed= 1, No= 0	2	2	2	2	1	2	2	2	2	2
	rear head restraints Yes w/ action = 2, Yes & Fixed =1, No=0	1	2	2	1	2	2	2	2	2	1
	Rear seat split: Yes= 1, No= 0	1	1	1	1	1	0	1	0	1	0
	Rear armrest: Yes= 1, No= 0	1	1	1	1	1	1	1	1	1	0
	Seat trim: Leather=3, Vinyl=2, cloth= 1	2	2	3	3	3	3	3	3	3	3
	Heated Seat: Driver & Pass= 2, Driver = 1, No=0	2	2	2	2	2	0	2	0	0	0

Occupant Comfort	Front legroom	42.3	41.2	40.7	42.8	41.3	41.6	42.4	43.1	43.1	43
	Rear legroom	37	38.7	39.6	36	39	41.1	36.4	38.7	37.7	23.7
	Third row legroom	0	36.3	0	0	0	0	0	0	0	0
	Front headroom	38.7	39.6	40	40.5	40.1	39.2	37.3	38.4	38.6	37.4
	Rear headroom	37.8	39.7	39.3	37.3	39.6	37.4	37.5	38.6	36.4	33.3
	third row headroom	0	37.8	0	0	0	0	0	0	0	0
	Front hip room	54.1	58	54.8	53	63.8	57.3	50.1	0	0	0
	Rear hip room	53.6	58	56.1	54.7	63.1	58	51.2	0	0	0
	Third row hip room	0	50.2	0	0	0	0	0	0	0	0
	Front shoulder room	56.9	63.3	58.9	57.6	65.8	60.6	52.5	58.3	56.4	55.2
	Rear shoulder room	55.6	63.4	58.8	57	65.8	60.3	53.7	58.3	56.7	51.5
	Third row shoulder room	0	52.3	0	0	0	0	0	0	0	0
	Passenger volume cu. Ft	99	158	108	102	122	113	90	80	99	65
Entertainment	Radio: Yes:1, No:0	1	1	1	1	1	1	1	1	1	1
	Cassette player: Yes:1, No:0	0	0	0	0	0	0	0	0	0	0
	CD player: Yes:1, No:0	1	1	1	1	1	1	1	1	1	1
	CD Changer: Yes:1, No:0	1	1	0	0	0	0	1	1	1	0
	MP3 capability: Yes:1, No:0	1	1	1	0	1	0	0	0	0	1
	Rear seat audio control: Yes:1, No:0	0	1	0	0	0	0	0	0	0	0
	# of Speakers	6	9	6	4	7	4	6	8	4	6
	Speed-Sensitive Volume Yes:1, No: 0	1	1	1	1	1	1	1	1	1	0
	entertainment system: Yes=1, No=0	0	1	1	0	1	0	0	0	0	0
	1st row LCD screen: Yes=1, No=0	1	0	1	1	0	0	1	1	1	1
Safety	airbags, frontal Driver & Passenger = 1 Driver only = 0	1	1	1	1	1	1	1	1	1	1
	airbags, side impact – Curtain: yes = 1, No=0	1	1	1	1	0	0	1	1	1	0
	occupancy sensor Front & rear=2, Front= 1, No= 0	1	0	1	1	1	1	1	1	1	1
	height adjustable seatbelts: Front & rear =1 front = 0	0	1	0	0	1	0	0	0	0	0
	Headlights: Halogen = 1, Incandescent = 0	1	1	1	1	1	1	1	1	1	1
	Exterior light control Auto =2, Manual	2	2	2	2	2	2	1	2	2	2

	=1, No = 0										
	delay-off headlamps: Yes=1, No=0	1	1	1	1	1	1	0	1	1	1
	daytime running lights: Yes=1, No=0	0	0	1	0	0	0	1	0	0	1
	door curb lights: Yes=1,No=0	0	1	0	0	1	1	1	0	1	1
	Illuminated entry: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1
	parking assist: Yes=1, No=0	0	1	0	0	0	1	1	1	1	1
Security	remote keyless entry: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1
	Panic alarm: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1
	Door locks: Power = 1, manual= 0	1	1	1	1	1	1	1	1	1	1
	rear child safety door locks: Yes=1, No=0	1	1	1	1	1	1	1	1	1	0
	content theft deterrent alarm system: Yes=1, No=0	1	0	1	1	1	1	1	1	1	1
	ignition disable: Yes=1, No=0	1	1	1	1	1	1	1	1	1	1
Ventilation	air conditioning, front Auto:1: Manual =0	1	1	1	1	1	1	1	1	1	1
	Air filter: Yes = 1, no=0	0	0	1	1	0	0	1	1	1	1
	Under seat ducts: Yes=1, No = 0	1	1	1	1	1	1	1	1	1	0
	Air conditioning rear: Yes=1, No = 0	0	1	0	0	0	0	0	0	0	0
Exterior Dimensions	Length. In.	190.5	207.5	186.5	194.3	223.8	215.4	183.8	205.3	193.1	188.6
	Width In	72.2	82.2	75.8	73.2	78.9	78.2	70.4	73.2	71.6	74.5
	Height In	57.1	77.8	67.5	56.1	73.5	58.6	56.7	57.3	57	52
	Exterior Box length	0	0	0	0	66	0	0	0	0	0
Engine	Size	3.5	5.4	3.5	3.9	5.4	4.6	3	4.2	3	4.2
	Hybrid = 2, Gas = 1	1	2	1	1	1	1	1	1	1	1
	# of Cylinders	6	8	6	8	8	8	6	8	6	8
	Horsepower	263	300	265	280	300	239	227	294	235	300
	torque	249	365	250	286	265	287	206	303	216	310
Fuel Economy	city mpg	19	15	18	18	15	17	18	18	19	18
	highway mpg	27	20	25	25	19	25	24	27	28	27
	weight - lb.	3469	5892	4220	3772	5370	4310	3516	3779	3760	3671
	fuel tank - gal	17.5	28	19	18	30	19	16	22.3	18.4	18.7
Trans.	Auto=1, Manual=0	1	1	1	1	1	1	5	1	1	1
	# of gears	6	6	6	5	4	4	0	6	6	6

Braking	4 wheel disc: yes=1, No=0	1	1	1	1	1	1	1	1	1	1
	2 disk / 2 Drum: yes=1, No=0	0	0	0	0	0	0	0	0	0	0
slide breaking	anti-lock braking system (ABS): yes = 1, no = 0	1	1	1	1	1	1	1	1	1	1
Drive Type	Four wheel = 2, Front = 1, Rear = 0	2	2	1	0	0	0	1	0	0	0
Power mechanism	Front windows: Auto= 1, manual = 0	1	1	1	1	1	1	1	1	1	1
	Rear windows: Auto= 1 manual = 0	1	1	1	1	1	1	1	1	1	1
	door locks: Auto= 1, manual = 0	1	1	1	1	1	1	1	1	1	1
	1-touch window down: Yes = 1, No= 0	1	1	1	1	1	1	1	1	1	1
Acceleration	0-60 - Second	6	7.9	7.7	6.3	8.4	8.5	6.6	6.4	7.7	5.8
	1/4 mile time - Second	14.5	16.2	15.9	14.8	16.2	16.3	15.2	14.8	15.9	14.5
	1/4 mile speed - mph	100	82	92	96	89	85	87	95	86	97
	lateral acceleration (g)	0.9	0.7	0.8	0.9	0.8	0.8	0.9	0.9	0.9	0.9
	slalom speed - mph	61	52	57	60	55	57	60	60	60	60
Handling	Wheelbase - In	107.4	118.8	111.2	114.5	138.5	117.7	106.7	124.4	114.5	108.3
	Front track- in	61.6	66.9	65.1	60.5	67	63.4	59.9	61.3	60.4	59.2
	Rear track - in	61.3	67.1	64.9	60.8	67	65.9	60.8	60.9	60.7	59
	Turning radius - in	18.6	19.4	19.7	19	22.5	20.2	17.8	19.8	18.9	18.1
luggage volume	Min volume - cu. Ft	15.8	18.3	31.8	13.5	0	21.1	16	16.4	14.1	10.6
	Max volume - cu. Ft	15.8	104.8	69	13.5	47.9	21.1	16	16.4	28.6	10.6
Tire	Radius, in	17	18	18	17	18	17	16	18	17	18
Access to vehicle	# of Doors	4	4	4	4	4	4	4	4	4	2
pickup box	Length	0	0	0	0	60.3	0	0	0	0	0
	Width	0	0	0	0	22.3	0	0	0	0	0

APPENDIX I – B
Product Family Exclusive Functions and Function Attributes– Case Study

Ford Motor Company

	Functions	Hitch back door	4 X4 Drive	Driving Assistance / GPS	Hybrid Engine	Heavy duty	Open Roof - Convertible	Pick-up with double cabin-Crew Cab	Wagon	low end class	High-End Class	unique Platform segment
		Exclusive functions/Marketable										
	Function attribute	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0	Yes =1, No=0
Family A - Ford Product Family	Compact Size Pick-up - Ranger	0	0	0	0	0	0	0	0	1	0	1
	Compact SUV - Escape	0	1	0	1	0	0	0	0	1	0	1
	Compact-Size Vehicle Focus	1	0	0	0	0	0	0	0	1	0	0
	Full-size Van - Freestar	0	0	0	0	0	0	0	0	1	0	1
	Full-Size Pickup - F Truck	0	1	0	0	1	0	1	0	1	0	0
	Full-Size SUV - Expedition	0	1	0	0	1	0	0	0	1	0	0
	Full-Size Vehicle - Taurus	1	0	0	0	0	0	0	1	1	0	0
	Sport - Thunderbird	0	0	0	0	0	1	0	0	1	0	0
	Mid-Size SUV - Explorer	0	1	0	0	0	0	0	0	1	0	1
	Mid-Size Vehicle - Fusion	0	0	0	0	0	0	0	0	1	0	0
	Sport Vehicle - Mustang	0	0	0	0	0	1	0	0	1	0	0
Family B - Lincoln Product Family	Mid-Size vehicle - MKZ	0	0	1	0	0	0	0	0	0	1	0
	Full-Size SUV - Navigator	0	0	0	0	0	0	0	0	0	1	0
	Mid-Size crossover - MKX	0	0	1	0	0	0	0	0	0	1	1
	Mid-size vehicle - LS	0	0	0	0	0	0	0	0	0	1	0
	Full-size pick-up - Mark LT	0	0	0	1	0	0	1	0	0	1	0
	Full-size vehicle – Town car	0	0	0	0	0	0	0	0	0	1	0
Family C - Jaguar Product Family	Compact-Size Vehicle - X Type	0	0	0	0	0	0	0	1	0	1	0
	Full-Size Vehicle - XJ	0	0	0	0	0	0	0	0	0	1	0
	Executive - S Type	0	0	0	0	0	0	0	0	0	1	1
	Sport Vehicle - XK	0	0	1	0	0	1	0	0	0	1	0

Vita Auctoris

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