ENHANCING THE CONCEPTUAL DESIGN PROCESS OF AUTOMOTIVE EXTERIOR SYSTEMS

by

David Diaz Dominguez

B.S. Mechanical Engineering and Management (2002)
Instituto Tecnológico y de Estudios Superiores de Monterrey

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

June 2011

Signature of Author ______________________________

David Diaz Dominguez
System Design and Management Program
June, 2011

Certified by ______________________________

Donna H. Rhodes
Thesis Supervisor
Senior Lecturer, Engineering Systems Division
Principal Research Scientist, SEAri and LAI

Accepted by ______________________________

Patrick Hale
Director - System Design and Management Program
Senior Lecturer, Engineering Systems Division

This Page is Intentionally Left Blank

To my beloved wife Sory, the cornerstone of my life

To my Mom and Dad, Tomy and David

To my brother Héctor

This Page is Intentionally Left Blank

ENHANCING THE CONCEPTUAL DESIGN PROCESS OF AUTOMOTIVE EXTERIOR SYSTEMS

by

David Diaz Dominguez

Submitted to the System Design and Management Program on May 03, 2011 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management

Abstract

Product development cycles in the automotive industry are being reduced and competition is more demanding than ever before. To be successful in this environment, Original Equipment Manufacturers need a product development process that delivers best-in-class value, at a competitive cost and with the shortest lead time. Within the development process, the conceptual design is the most important phase in the delivery of a no-compromise design solution. In this phase, design teams have the largest amount of latitude to create value in the product, but they also face high levels of uncertainty and incomplete information to make decisions.

At a high level, the conceptual design phase encompasses four major steps. In the first step, value is defined from the stakeholder perspective and system objectives are defined. The second step involves a divergent process in which design space is explored and several concept alternatives are generated to meet the system objectives. The third is a convergent process in which design alternatives are matured, evaluated and one is selected. In the fourth step, the architecture of the system is articulated.

The intended impact of this thesis is to enhance the value delivered in the conceptual design phase and prevent waste in downstream activities within the product development process. To achieve this, the conceptual design processes of a major automotive manufacturer were studied to identify the problems that constrain value delivery and generate waste. The findings of this study and the exploration of existing concept development frameworks were synthesized in a concept development methodology focused on automotive Exterior Systems.

Thesis Supervisor: Dr. Donna H. Rhodes
Senior Lecturer - Engineering Systems Division
Principal Research Scientist, SEAri and LAI
Massachusetts Institute of Technology

Acknowledgements

Attending the System Design and Management (SDM) program at MIT has been a challenging and fascinating journey. The SDM program allowed me to grow in both personal and professional areas by providing me with invaluable experiences and exposure to MIT's vast knowledge assets. This thesis represents the conclusion of this wonderful experience. I am grateful to all who helped me to complete both the program and the thesis. In the following lines, I will try to express my gratitude to those who were instrumental in the completion of this journey...

> *Sory,* I cannot thank enough your love, patience and unconditional support. I would not have been able to do it without you. Thanks for encouraging me to pursue and fulfill a life's dream.
>
> *Mom* and *Dad*, thanks for your example of hard work and perseverance.
>
> My dear brother *Héctor*, thanks for your support and friendship.

I would like to specially thank:

> My thesis advisor *Donna Rhodes*, whose guidance and insightful feedback allowed me to complete this thesis. Thanks for your time and patience.
>
> *Marcos Perez* whose vision and inspiring leadership promoted the SDM initiative in our company. Thanks for your trust.
>
> *Alex Ayala*, my mentor. Thanks for dedicating time to listen my ideas and for challenging me to raise the bar in everything I do.
>
> My partner in this journey, *Raul Pinillos*, whose advice, hard work and friendship was fundamental in this achievement.
>
> *Jose Luis Lopez* for his advice and support in the early years of my career in the company.
>
> The management team in PD Mexico for their feedback and support during the program.
>
> *Paul Jackowski,* for being supportive of my scholar duties. I appreciate your honest feedback that helped me to improve every day.
>
> *Ian McLaughlin* for his wise comments that allowed me to look at problems from different perspectives. I am grateful for the opportunity to learn from your knowledgeable and talented organization.

Adrian Aguirre and *Takahiro Endo*, our first SDM generation, whose efforts opened the doors of the SDM program.

Marcia Azpeitia, *Antonio Del Puerto*, *Adrian Díaz* and *Antonio Almazán*, SDM alumni, for their advice, help and friendship.

Pat Hale, *MIT faculty* and *SDM staff* for their guidance and support throughout the SDM program.

Lou T. for helping me to improve my writing skills.

My friends and relatives who were always supportive.

Table of contents

List of Figures

List of Tables

List of Equations

List of Acronyms

AOEM: Automotive Original Equipment Manufacturer

APEAL: Automotive Performance Execution and Layout

BRIC: Brazil, Russia, India and China

CAD: Computer Aided Design

CAE: Computer Aided Engineering

CAM: Computer Aided Manufacturing

CE: Chief Engineer

CFD: Computational Fluid Dynamics

DMM: Domain Mapping Matrix

DSM: Design Structure Matrix

ESM: Engineering System Matrix

Euro NCAP: European New Car Assessment Programme

IIHS: Insurance Institute for Highway Safety

JLR: Jaguar and Land Rover

NHTSA: National Highway Traffic Safety Administration

NIST: National Institute of Standards and Technology

OEM: Original Equipment Manufacturer

PDP: Product Development Process

QFD: Quality Function Deployment

R&D: Research and Development

SAE: Society of Automotive Engineers

SME: Subject Matter Expert

TRIZ: Theory of Inventive Problem Solving

UMR: University Of Missouri Rolla

Chapter 1 - Introduction

1.1 The Conceptual Design Phase in the Product Development Process

Conceptual design encompasses the initial activities in the product development process that start with the identification of customer needs and deliver the product architecture. It is recognized as one of the principal steps in several product development frameworks. Two of these frameworks are described in the following pages in order to give an overview of the activities that the conceptual design process involves and to give a sense of the sequence in which they are executed.

Ulrich and Eppinger (2008) decomposed the product development process in six phases: *Planning*, *Concept Development*, *System-level design*, *Detail design*, *Testing/refinement* and *Production ramp-up*. In the *Planning* phase, the organization identifies market opportunities for new products and evaluates how they will fit in the product portfolio. Once this process is completed, individual projects are defined for each product (assumptions, goals and constraints are determined). Also, the organization allocates resources and sets up the project timing.

During the second phase, *Concept Development*, customer needs are identified and translated into requirements. Then, the team generates multiple ideas and identifies several solutions to the design problem. These design alternatives are then evaluated in order to select one or more candidates that will be developed into the system architecture. In the *System-level design* phase, the system architecture of the product is defined: a concept is selected; subsystems and major interfaces are decided. In addition, a geometric representation of the system and a high level decomposition are developed. Next, in the *Detail design* phase, the specifications, geometry and tolerances of all components are completed. The *Testing and refinement* phase involves the construction and evaluation of prototypes to verify that the product meets the design intent. In the final phase, *Production* *ramp-up*, the manufacturing process is fully implemented. Production processes are evaluated and gradually improved until the product is launched.

In the framework developed by Kroll et al. (2001), the engineering design process is decomposed in three main stages: *Need Identification / Analysis*, *Conceptual Design* and *Realization* (Figure 1). The first stage includes those activities that help understand the *real* needs of the market, the constraints that delineate the solution space and the functions required from the system to be designed. Identifying the *real* need refers to the means used to find the solution-neutral problem in order to avoid missing the optimal solution due to a biased problem statement.

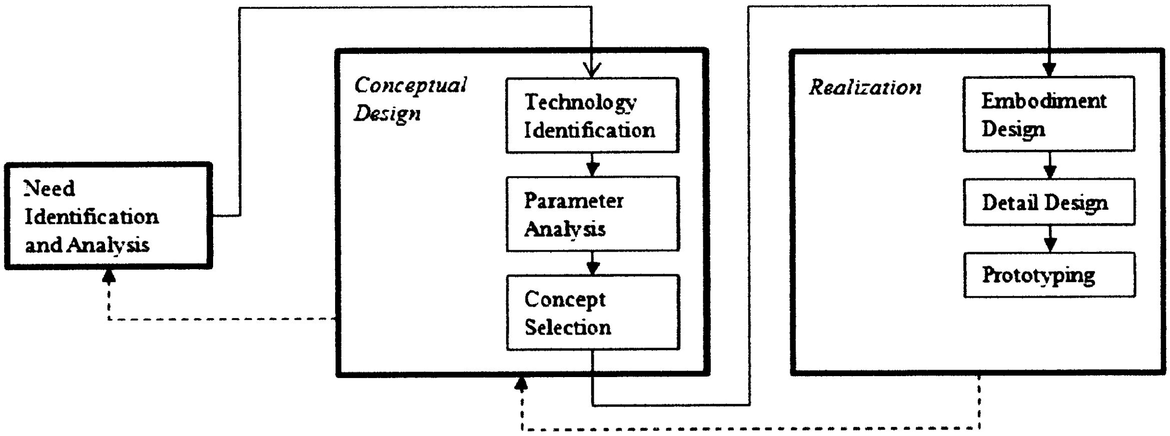


Figure 1 - Overview of the engineering design process (Kroll, Condoor, & Jansson, 2001)

In the second stage, *Conceptual Design*, ideas that satisfy the need are generated and selected. This stage can be further decomposed in three steps: *Technology Identification*, *Parameter Analysis*, and *Concept Selection.* The first step refers to the process of exploring the available technologies that can be implemented to solve the problem and also sets the starting point for the next step. *Parameter Analysis* is an iterative process that begins with identifying the parameters and understanding the physics governing the technologies explored. This process involves looking at the problem from different perspectives. Afterwards, creativity is applied to generate a configuration (application) that implements the concept. Finally, the fitness of the configuration is evaluated relative to the requirements of the design problem. The process is repeated several times to develop several solutions. In the *Concept Selection* step, these solutions are evaluated and compared to determine which one should be implemented. Finally, the third stage (*Realization*) includes all the activities required to mature the selected concept and implement the design solution.

This thesis considers a simplified model of the conceptual design process (Figure 2). The inputs to this process come from a higher level system in the form of needs, constraints and assumptions. This model considers four major steps. In the first one, value is articulated by the stakeholders and translated into system requirements (*Value Definition*). In the second step, *Concept Generation*, divergent thought process is used to generate ideas (concepts) that satisfy system requirements. In this step, design space is explored within the boundaries received as inputs. *Concept Selection* is the third step. Here, a convergent thought process is used to reduce the number of alternatives based on the fitness of the concept relative to the elements valued by the stakeholders. During this process all concepts are evaluated and compared in order to select the best solution. These evaluations reduce uncertainty and help make decisions with lower risks. *System Architecture Definition* is the last step of this process. This step encompasses the activities to articulate the system decomposition: subsystems and interfaces are determined. The output of the conceptual design process (the architecture) becomes input for downstream processes: detailed design or conceptual design of lower order systems. This process has multiple feedback loops that recognize the possibility of iterations due to the discovery of new information.

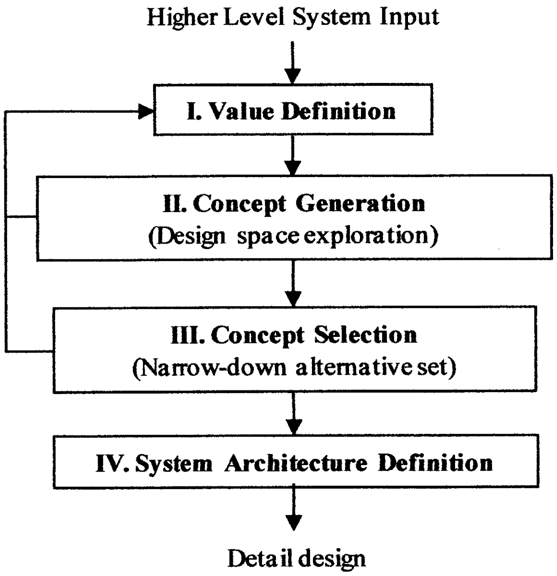


Figure 2 - Simplified Conceptual Design Process Map

1.2 Context: the automotive industry

During 2008 and 2009, the automotive industry experienced a severe crisis. The total revenue in the industry was reduced by 5.6% in 2008 and 15.7% in 2009 (IBISWorld, 2010). Figure 3 shows the revenue growth rate since 2006, including the expected rate for 2010. In the upcoming years, analysts expect gradual recovery driven by growth in emergent markets (BRIC[1]) and increasing demand for smaller and more efficient vehicles (Standard & Poor's, 2010). Management consulting firm Arthur D. Little considers two scenarios (high and low demand) for worldwide passenger car sales in the report "Future of Mobility 2020", published in 2009. The high demand scenario assumes growth rates in mature markets will recover to pre-crisis levels and reach double-digits in emergent markets (scenario A, Figure 4). On the other hand, the low demand scenario assumes that growth will be concentrated in emergent markets as demand in mature markets decreases (scenario B, Figure 4).

---

[1] BRIC: Brazil, Russia, India and China

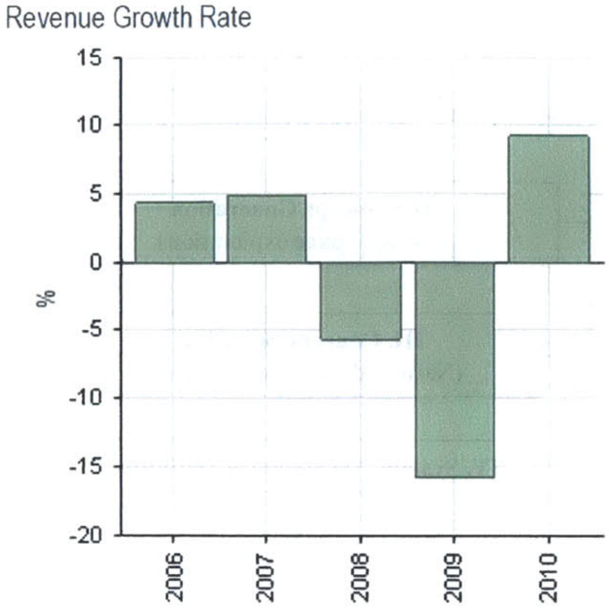


Figure 3 - Revenue growth rate, global automotive market (IBISWorld, 2010)

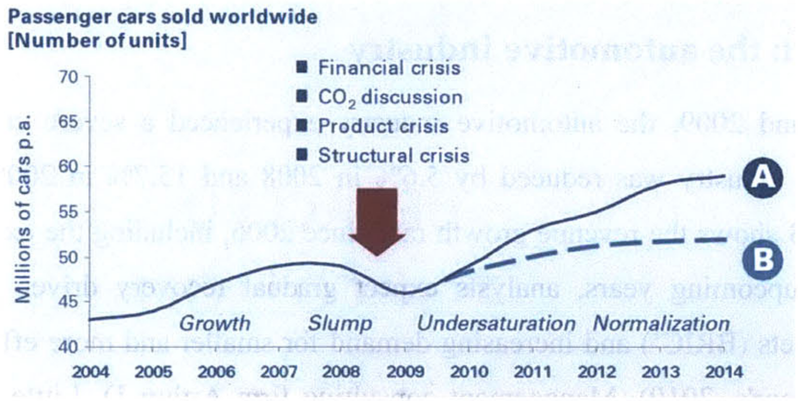


Figure 4 - Worldwide passenger car sales trend and forecasts toward 2014 (Arthur D. Little, 2009)

In addition to these recovery signals, two mega-trends can be identified in the automotive industry: accentuated global competition and increased complexity in value definition. In 2010, only 35.4% of the global market will be controlled by the five major automakers: Toyota, Volkswagen A.G., General Motors, Ford Motor Company and Honda. The remaining 64.6% will be distributed among the rest of the Original Equipment Manufacturers (OEMs), each with market share below 5% (IBISWorld, 2010). Automakers based in developed countries are trying to gain presence in growing markets like China, the largest vehicle market in 2009 (BBC News, 2010). By establishing joint-ventures, building assembly plants and R&D facilities within these countries, major OEMs are taking positions to compete for a share of these markets. For example, Ford Motor Company recently announced the expansion of its manufacturing facilities in India to launch eight new models (Financial Times, 2010). In 2010, GM started the construction of an advanced technical center in China (GM, 2010). Another example is Volkswagen, which has had a joint venture with the FAW Group in China since 2004 and is planning to expand its assembly facilities through 2013 (Edmunds, 2010).

On the other hand, OEMs from India, Korea and China are gradually gaining a portion of the market in the US and Europe. For example, the Korean automotive group Hyundai-Kia posted a 7.1% increase in market-share in the US during 2009, despite the market crisis (Standard & Poor's, 2010). Other companies are using acquisitions as part of their strategy to gain presence in mature markets: Indian Tata purchased JLR[2] in 2008 (Tata Motors, 2008) and Chinese Geely did the same with Volvo in 2010 (Reuters, 2010).

The perception of value in automotive products is becoming more complex. Fuel efficiency, aesthetics, craftsmanship, safety, reliability, technology, affordability and cost of ownership are some of the attributes that customers consider when purchasing a vehicles. In fact, organizations like J. D. Power and Consumer Reports use models with multiple attributes to evaluate automotive products. J. D. Power's 2010 APEAL[3] study considers ten weighted categories, totaling more than 80 vehicle attributes in its questionnaires (J. D. Power, 2010).

To succeed in this challenging environment, automakers must excel in all areas. In order to meet these expectations, developers require methods that facilitate achievement of design solutions with minimal tradeoffs. A fundamental enabler in this process is assurance of the correctness of the concept (i.e. "The right concept"), which is conceived in the early phases of the development process.

1.3 Motivation

---

[2] JLR: Jaguar, Land Rover

[3] APEAL: Automotive Performance Execution and Layout

Automotive Exterior Systems are the study subject for this thesis. The fact that these systems must meet both objective and subjective targets is particularly interesting and challenging. Durability, crash-worthiness, craftsmanship and manufacturability are some examples of the objective requirements. Subjective issues include design features required to achieve vehicle aesthetics. Also, exterior systems are key elements to differentiate the product in the market place and to appeal to customers. In order to keep the product up-to-date in a highly competitive environment, OEMs have gradually increased the frequency of exterior styling changes and enhanced the visual impact of these updates.

To illustrate this trend, the exterior changes in four vehicles from different manufacturers in the US mid-size car category were mapped in a time scale (Figure 5). In this figure, exterior changes are classified in three categories: *All new body, Major front/rear update* and *Minor front/rear update*. The first classification refers to major styling changes that affect all exterior systems and exterior dimensions. The second one encompasses major styling updates to the front (hood, fascia, headlamps, and grilles) and rear (tail lamps, fascia, and deck lid). In the third classification, styling changes are limited to the front/rear fascias, grilles and minor updates to the lighting systems. In the figure, it is noticeable that automakers in this segment are converging in launching product with an *all new body* each 4-5 years and a *front/rear update* in-between, 2-3 years after the product with an *all new body* is introduced.

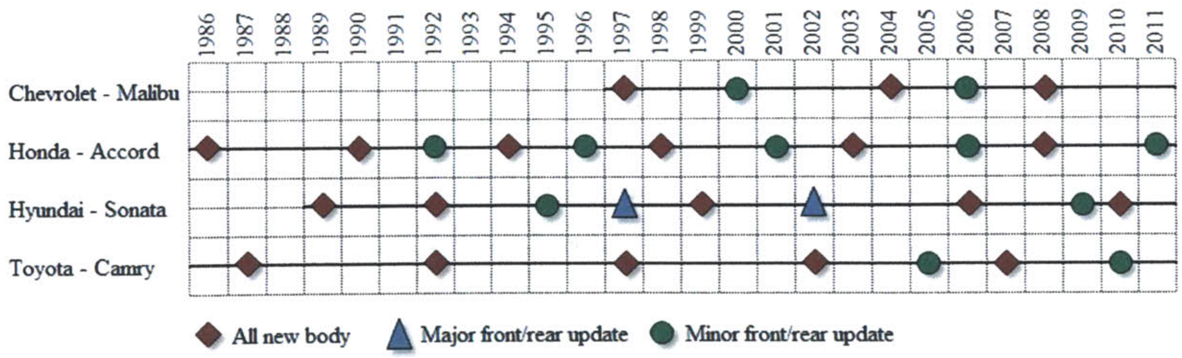


Figure 5 - Exterior styling changes in mid-size cars (US market)

Typically, there is tension between the appearance and functional requirements, trade-offs are often difficult. The increase in the pace of exterior changes and the need to maximize the visual impact of these updates while meeting multiple functional goals, exacerbate the frequency of trade-off conflicts during the development process.

It is inferred that the more design alternatives are explored, the higher the probability of finding a no-compromise solution to a given design problem. During the initial stages in automotive product development projects, it is easier to explore multiple design alternatives as the cost is minimal and design space has few constraints. Unfortunately, decisions must be made with incomplete information and high levels of uncertainty. This results in risks of rework in downstream activities if the team does not make the correct decisions during the initial stages of the project. To minimize these risks, the development process must recognize the elements of uncertainty in the system and deal with them as early in the process as possible. The early stages in the development process have great potential to improve the value delivered in the product and to reduce rework in the process. Generating and maturing design alternatives require resources and time, which are limited in a project. Therefore, there is need for efficient methods to manage alternatives that also allow maximization of design space exploration while considering the resources and time available.

The author has special interest in the conceptual design of automotive Exterior Systems because of his background and current job role as Studio Engineer in a major automotive OEM. In this position, the author actively participates in the generation and evaluation of concepts for body systems and performs as interface between the Styling work stream and the engineering community. The exposure to several phases in the product development (PD) process has helped the author acknowledge the potential of the conceptual design process to maximize the value delivered to the customer and prevent waste downstream in the PD process.

1.4 Research questions

In response to the author's motivation and interest in the conceptual design of automotive Exterior Systems, the following questions will be addressed in this thesis research:

1. Which methods to generate and select design alternatives maximize value to the stakeholders during the conceptualization of automotive Exterior Systems?

2. How to manage the elements of uncertainty during the conceptual design phase in order to prevent waste in downstream processes?

1.5 Research methodology

The research methodology for this thesis involved two major elements: a comprehensive literature review and the study of the process used in a major automotive OEM to conceptualize Exterior Systems. The literature review included system modeling and concept development frameworks. This survey provided insight on the many concept development methodologies that have been proposed. Given time constraints, the exploration of all these techniques was considered out of the scope of this thesis. Instead, the approach selected to address the research questions was to configure a concept development methodology customized for automotive Exterior Systems. To achieve this, a subset of the existing frameworks was selected to be further investigated. The selected frameworks include a system modeling tool, two concept generation methods and two concept selection methods.

The second major element, the study of the conceptualization methods in a major OEM, involved a review of the OEM's formal processes and interviews with subject matter experts in the organization. The analysis of the data obtained allowed identification of generic and OEM-specific concept development problems that constrain value delivery and generate waste in downstream processes.

This thesis synthesizes the theory foundations from the literature review and the findings from the OEM study into a concept development methodology that looks for maximization of value delivery and reduction of waste in downstream PD processes. Finally, an application example allowed refinement of the proposed methodology.

1.6 Thesis outline

The outline of the remainder of this thesis is described below to give the reader a high-level overview of the content of this document and help understanding the structure of the argument.

Chapter 2 reviews the literature used as foundation to develop the methodology proposed in this thesis. Three pillars are considered in this survey: System Modeling tools, Concept Generation Methods and Concept Selection frameworks. For the first pillar, this chapter examines the evolution of adjacency matrices as system modeling tools as well as the methods developed to analyze these models. Related to the second pillar, two concept generation techniques are discussed: the Morphological approach and the analogy method TRIZ. Finally, Set-based concurrent engineering and Pugh's controlled convergence are the frameworks surveyed for the third pillar, Concept Selection.

Chapter 3 provides a comprehensive description of the conceptual design process used in the automotive OEM under study to develop Exterior Systems and identifies concept development problems that limit value delivery and generate waste in downstream product development processes. The first part of this chapter sets the context for this thesis by discussing relevant aspects involved in the development of Exterior Systems in the automotive industry. Then, this chapter reviews the process used to develop concepts for Exterior Systems. This review describes the process to elicit value and provides insight on the *styling* and the *functional* aspects of the concept at multiple system levels. The analysis of these processes allowed the identification of generic and OEM-specific concept development problems.

Chapter 4 provides a layout of the proposed methodology and describes the first two major steps: Value Definition and Concept Generation. This chapter describes a matrix-based system modeling tool derived from Bartolomei's Engineering Systems Matrix (ESM) (2007) that is used throughout the methodology steps. In the Concept Generation step, the proposed method uses a Function DSM to breakdown a complex system into smaller elements to facilitate concept development efforts. In addition, the morphological approach is used to configure multiple concept alternatives and explore the design space. Moreover, this chapter provides a method to downsize the number of concept alternatives and define a manageable set that will be progressed and evaluated during the Concept Selection step. Finally, a summary of the actions that prevent concept development problems is provided.

Chapter 5 provides an in-depth description of the remaining two major steps in the methodology: Concept Selection and System Architecture Definition. For the Concept Selection step, this chapter describes a multi-stage selection process that considers a decision making process based on quantitative and qualitative assessments. The quantitative assessment involves the calculation of metrics and indicators that evaluate value delivery and uncertainty. An evaluation of the integrity of the concept is considered in the qualitative assessment. In addition, this chapter describes the figure of the Chief Engineer as the leader in the concept selection process and provides guidelines to conduct the concept selection discussion. Finally, a summary of the methodology elements that prevent concept development problems that limit value delivery and generate waste in downstream processes is provided.

Chapter 6 describes an application example of the methodology. In this example, the proposed methodology is used in the concept development of an exterior rear-end system in a vehicle with crossover utility architecture. The scope of this application example is limited to the definition of value at system level, the identification of concept layers, the configuration of concept alternatives for one of the concept layers and the quantitative assessment of this alternative set.

Chapter 7 reviews the achievements of this methodology and the challenges that its implementation involves. Finally, this chapter provides a list of topics derived from this thesis research that will be considered as future work.

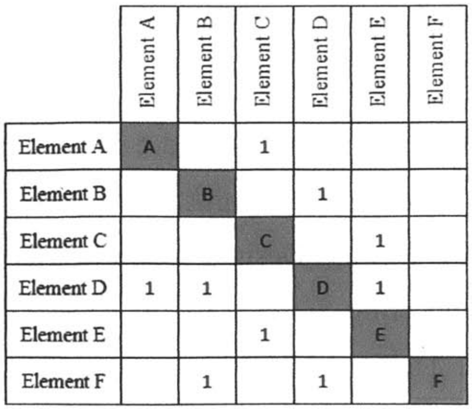
Chapter 2 – Literature Review

The methodology proposed in Chapters 4 and 5 builds upon system modeling, concept generation and concept selection frameworks. This chapter surveys these methodologies, their applications and limitations. Design Structure Matrix (DSM), Domain Mapping Matrix (DMM) and Engineering Systems Matrix (ESM) are the system modeling tools described in this survey. The concept generation techniques explored are morphological matrices and analogy methods. Finally, this chapter examines Pugh's method and Set-Based Design as concept selection frameworks.

2.1 System modeling tools

2.1.1 The Design Structure Matrix (DSM)

DSM is a systems modeling framework first formalized by Steward (1981) that can represent the relationships within the elements of a system or process using an adjacency matrix. The DSM tool is a square matrix with identical rows and columns. The cells in the diagonal of the matrix represent the elements of the system (nodes) and the off-diagonal cells describe the relationships among these. Typically, dependencies between nodes are represented with "1" or "X". On the other hand, if there is no connection between the elements, cells are left blank. Figure 6 illustrates an example of a DSM matrix. We can find the inputs of a node when reading across its row and the outputs if reading down its column. Using the example in Figure 6, Element D requires inputs from A, B and E and provides outputs to Elements B and F.



	Element A	Element B	Element C	Element D	Element E	Element F
Element A	A		1			
Element B		B		1		
Element C			C		1	
Element D	1	1		D	1	
Element E			1		E	
Element F		1		1		F

Figure 6 - DSM matrix

The DSM matrix has been used to model relationships between people, tasks, components and parameters. Browning (2001) classified DSM applications in two groups: static and time-based. Static DSMs model dependencies between nodes that co-exist at the same point in time. Component and People based DSMs belong to this group. The component based DSM (also known as architecture DSM) represent the relationships among components in a product or system. The People-Based DSM models the interactions between individuals or groups within an organization. Static DSM matrices can represent several types of dependencies. If one wishes to represent a single type of relationship, "1" or "X" are commonly used to fill in off-diagonal cells. On the other hand, several nomenclatures have been used to represent multiple types and levels of dependency. For example "H", "M" and "L" for high, medium and low or "S", "E", "I" and "M" for spatial, energy, information and material (Pimmler and Eppinger, 1994).

Time-based DSMs are the second group in Browning's (2001) taxonomy. In these matrices, there are sequence or flow dependencies among the nodes. This group can be further divided in two categories: Activity and Parameter-based. In the Activity-based DSMs the nodes are the tasks in a process or project and the off-diagonal cells are used to represent sequence relationships. Figure 7 shows the representation of parallel, sequential and coupled tasks in a DSM. Parallel tasks are the ones whose inputs are independent from each other and can be performed simultaneously if desired. Sequential tasks have precedence relationships between them, one of the tasks require the output of the other to start. Coupled tasks are interdependent, in other words, both tasks need the output of the other as inputs, which implies two iterations at least.

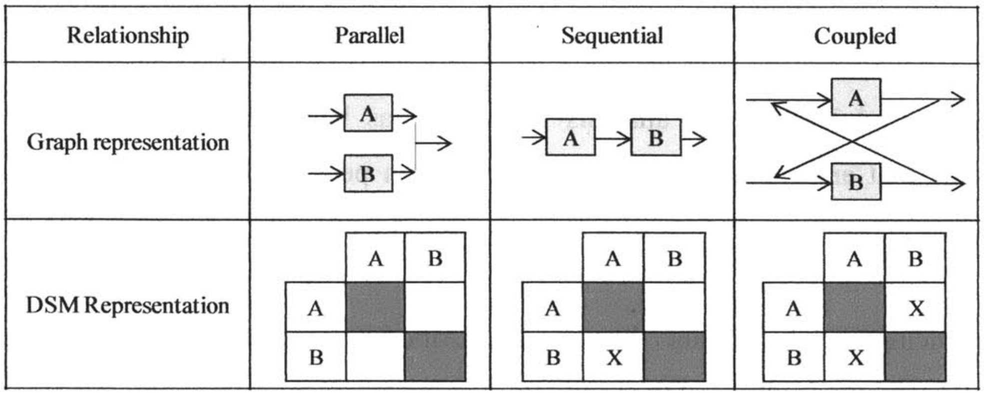


Figure 7 - DSM representation of sequence relationships (Kalligeros, 2006)

Parameter based DSMs model the relationships between parameters in the design of a system. These models describe the information flow to define the design parameters and the precedence relationships between them. Figure 8 shows an extract from the DSM that Black et al. (1990) used to analyze the design process of a brake system. In this DSM, to define the parameter "rotor diameter" (5), we need to know the customer requirements (1), "wheel torque" (2), "pedal's mechanical advantage" (3), the system level parameters (4) and the coefficient of friction of the linings (7).

	1	2	3	4	5	6	7
1. Customer requirements	▨						
2. Wheel torque		▨		X			
3. Pedal mech. advant.	X		▨	X	X		
4. System level parameters	X			▨			
5. Rotor diameter	X	X	X	X	▨		X
6. ABS modulator displ.						▨	
7. Lining coeff. frict.			X	X	X		▨
8. Piston - Rear size		X		X			

Figure 8 - Parameter DSM (modified from Black et Al, 1990)

In addition to help the visualization of relationships between elements in the system, DSM matrices have been used for other analyses. Clustering, sequencing, tearing and banding are some of the techniques that have been developed for DSM matrices (Bartolomei, Cokus, Dahlgren, de Neufville, Maldonado, & Wilds, 2007). The clustering technique is used to analyze Static DSMs. It applies graph cluster algorithms to group nodes with high levels of interaction along the matrix diagonal. Some examples of these cluster algorithms are the ones proposed by McCormick (1972), Fernandez (1998) and Thebeau (2001). In component-based DSMs, this analysis technique has been used to identify groups of components that are candidates to form modules. In people-based DSMs clustering has been applied to restructure teams in an organization (McCord & Eppinger, 1993).

The sequencing technique (also known as Partitioning) is used to analyze time-based DSMs. This method reorders the rows and columns in the matrix to maximize feed-forward flow in the sequence while minimizing the impact of feedback loops and iterations. Several algorithms have been developed for doing the sequencing analysis: Path searching, Powers of the Adjacency Matrix Method, the Reach-ability Matrix Method and the Triangularization Algorithm.

The tearing analysis (Steward, 1981) is used in time-based DSMs and consists in finding the set of feedback interactions (marks above the diagonal) that if removed, yield a matrix with all marks in the lower triangle. The analyst removes feedback iterations by making assumptions about the process, selecting the “least damaging” assumptions first. The web portal DSMweb.org recommends minimizing the number of tears applied and to enclose these to the smallest iteration blocks along the matrix diagonal. This would help to minimize the number of “guesses” and to reduce the number of iterations within the iteration blocks.

The banding analysis is applied to both time-based and static DSMs to identify nodes or groups of nodes that are independent by reordering rows and columns and assigning alternating colors to the rows in the matrix. In task-based DSMs, banding can help to identify the tasks or groups of tasks that can occur simultaneously. In component-based DSMs, a designer can use banding to find which components are independent and plan testing accordingly (Bartolomei, Cokus, Dahlgren, de Neufville, Maldonado, & Wilds, 2007).

2.1.2 The Domain Mapping Matrix (DMM)

DSM matrices are useful to represent interactions between elements in a single domain: system components, organizations, tasks in a project and parameters in a design. But, these matrices cannot be used to model multi-domain interactions. Recognizing this limitation, Danilovic and Browning (2007) introduced the Domain Mapping Matrix (DMM), a rectangular matrix (m x n) that model interactions between elements of different domains. Also, they proposed a framework that combines the use of square (DSMs, n x n) and rectangular (DMM, m x n) matrices to model multiple domains in a product development project (Figure 9). In this framework five domains are considered: goals, product, process, organization and tools. Five DSMs model inter-domain relationships and ten DMM matrices are used to represent multi-domain interactions. Each DSM can be analyzed individually using sequencing or clustering techniques. On the other hand, to analyze DMMs only clustering techniques have been applied (Danilovic & Browning, 2007).

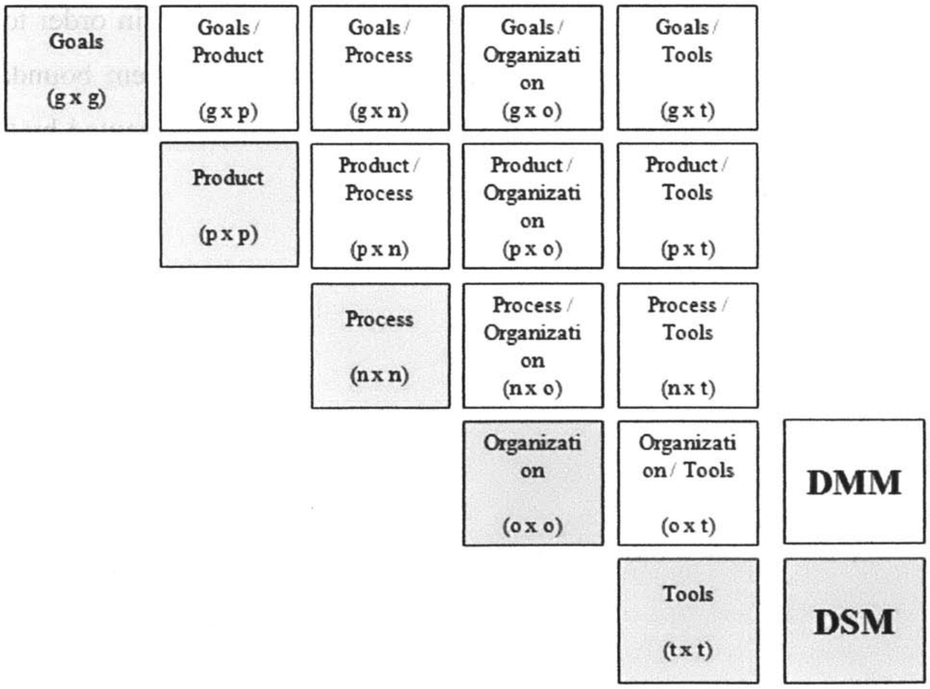


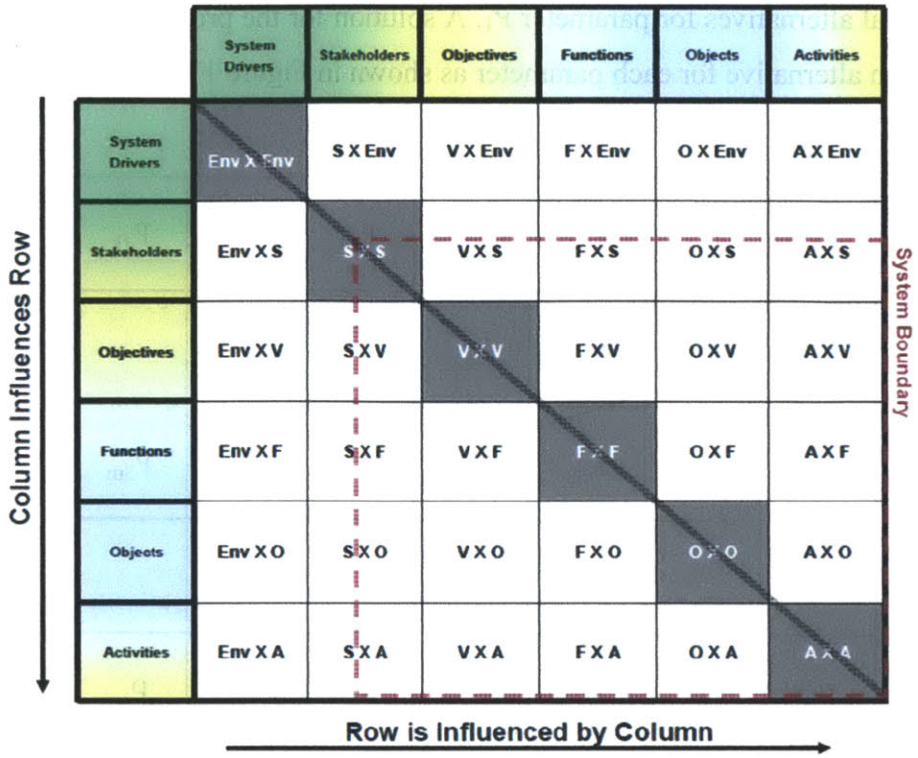
Figure 9 - Multi-domain framework combining DMMs and DSMs to model a PD project (Danilovic & Browning, 2007)

2.1.3 Engineering Systems Matrix (ESM)

Related to DSM and DMM tools, Bartolomei (2007) proposed the Engineering Systems Matrix as a framework to model Engineering Systems. The ESM is a square matrix with identical rows and columns and six classes of nodes: System Drivers, Stakeholders, Objectives, Functions, Objects and Activities (Figure 10). *System drivers* are the elements outside of the system boundaries that influence or are influenced by the system and cannot be controlled by the human components of the system. These influences can be economical (cost of raw materials), political (new regulations) or technological (innovations in competitive products).

The *Stakeholders* class represents the human elements of the system. These can be external or internal to the system. External stakeholders are the ones that affect or are affected by the system but do not have control over the elements inside the system boundaries. On the other hand, the internal stakeholders set the objectives of the system, manage the resources, make decisions and execute the activities.

The *Objectives* class represents the goals of the system as defined by the stakeholders. The *Functions* class describes the operations the system must accomplish in order to meet the objectives. The *Objects* are the physical components within the system boundaries. The *Activities* are the processes and tasks related to the system that are executed by the human elements of the system.



	System Drivers	Stakeholders	Objectives	Functions	Objects	Activities
System Drivers	Env X Env	S X Env	V X Env	F X Env	O X Env	A X Env
Stakeholders	Env X S	S X S	V X S	F X S	O X S	A X S
Objectives	Env X V	S X V	V X V	F X V	O X V	A X V
Functions	Env X F	S X F	V X F	F X F	O X F	A X F
Objects	Env X O	S X O	V X O	F X O	O X O	A X O
Activities	Env X A	S X A	V X A	F X A	O X A	A X A

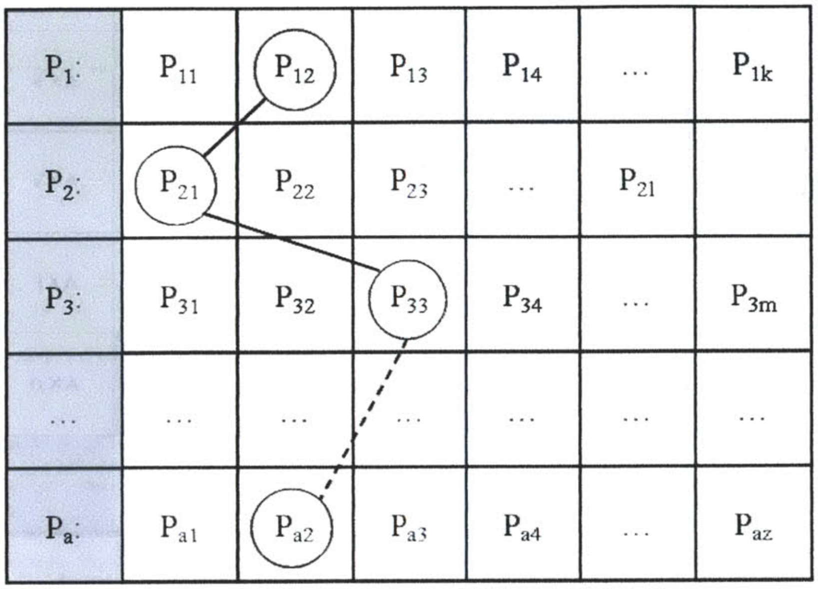
Figure 10 - Engineering Systems Matrix (Bartolomei J. , 2007)

As shown in Figure 10, the ESM matrix is an array of DMM and DSM matrices. DSM matrices (6) are located along the diagonal and represent the interaction within domains. The rest of the matrices (30) are DMMs that describe the interactions across domains. These matrices can be analyzed separately using the techniques described earlier in this chapter.

2.2 Concept generation methods

2.2.1 Morphological Matrix

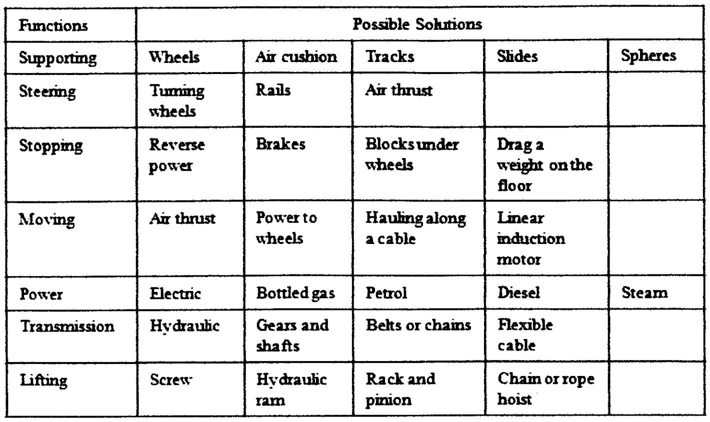
This methodology was first introduced by Zwicky (1969) as a method to explore the potential solutions to a problem with multiple parameters. Figure 11 shows the generic form of Zwicky's tool, the *Morphological Box*. In this chart, the first column lists the relevant parameters of a problem $P_{1,2,3,\ \ldots,a}$. The cells to the right correspond to all the potential alternatives. For example, taking the first row, P_{11}, P_{12}, P_{13} ... P_{1k} corresponds to all the potential alternatives for parameter P_1. A solution for the problem can be configured by selecting an alternative for each parameter as shown in Figure 11 (circled alternatives).



P_1:	P_{11}	P_{12}	P_{13}	P_{14}	...	P_{1k}
P_2:	P_{21}	P_{22}	P_{23}	...	P_{21}	
P_3:	P_{31}	P_{32}	P_{33}	P_{34}	...	P_{3m}
...	...	...	...	...	...	...
P_a:	P_{a1}	P_{a2}	P_{a3}	P_{a4}	...	P_{az}

Figure 11 – Morphological box, modified from Zwicky (1969)

Zwicky's tool has evolved into the method for generating and organizing solution alternatives known as morphological matrices (also known as morphological charts). In this technique, the first step is to determine the solution-neutral functions of the system (functions that do not imply the use of a specific design solution). For example, the function *braking* cannot be considered a solution neutral function as it involves the use of brakes as the instrument to cease the motion of the system. The solution-neutral function would be *stopping*. Once the functions of the system are determined, the design team should identify several design solutions for each using techniques like brainstorming or benchmarking. This information is then organized using a matrix form. The first column lists the solution-neutral functions and the cells to the right in the row show the design alternatives identified. These alternatives are represented using text (see Figure 12) and/or graphics. Once the matrix is populated, the next step is to select a design solution for each function in order to set a concept configuration. Different configurations can be achieved by using different combinations of design alternatives.

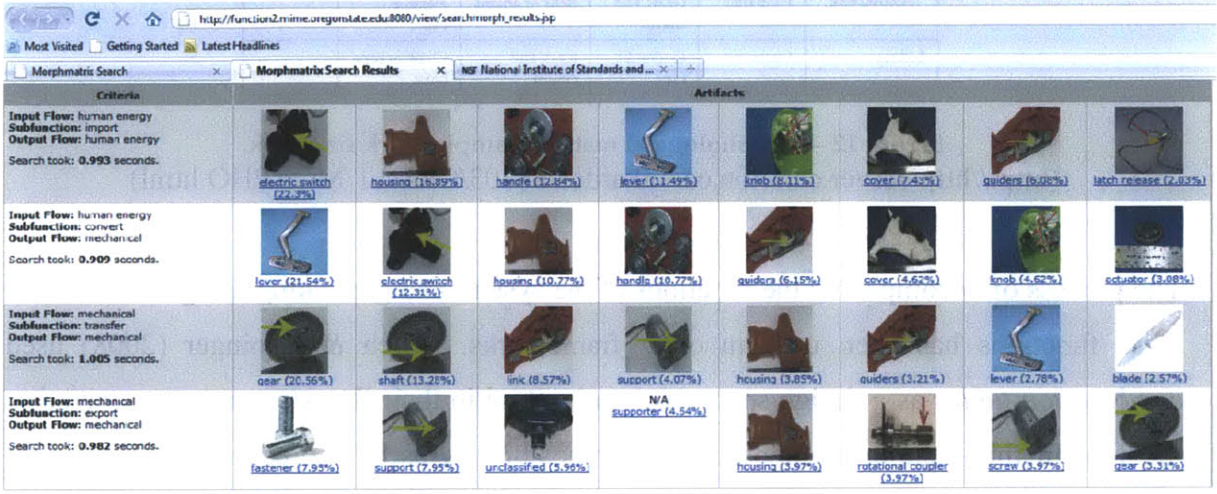


Functions	Possible Solutions				
Supporting	Wheels	Air cushion	Tracks	Slides	Spheres
Steering	Turning wheels	Rails	Air thrust		
Stopping	Reverse power	Brakes	Blocks under wheels	Drag a weight on the floor	
Moving	Air thrust	Power to wheels	Hauling along a cable	Linear induction motor	
Power	Electric	Bottled gas	Petrol	Diesel	Steam
Transmission	Hydraulic	Gears and shafts	Belts or chains	Flexible cable	
Lifting	Screw	Hydraulic ram	Rack and pinion	Chain or rope hoist	

Figure 12 - Morphological matrix example: Fork lift truck.
(http://http-server.carleton.ca/~gkardos/88403/CREAT/MORPHO.html)

The process of decomposing the functions of the system and generating design solutions to these functions has been used in other frameworks. Ulrich & Eppinger (2008) used *combination tables* as a design space exploration tool in their five step concept generation method. In this technique, functional decomposition is used to break down a complex problem into simpler sub-problems. Then, using benchmarking, lead user interviews, expert consultation and other idea generation tools, multiple design alternatives are configured to address each sub-problem. The next step is to use *combination tables* to link the design alternatives and configure solutions for the complex design problem.

Morphological charts have been associated with design repositories and automated concept generators. The tools developed by the Design Engineering Lab at Oregon State University allow generating morphological charts using a web-based design repository. This design database was developed by a joint effort from researchers from the University of Missouri Rolla (UMR), The University of Texas at Austin and the National Institute of Standards and Technology (NIST). It stores design information of the components from more than 5800 artifacts. This data stored includes functional decomposition, general dimensions, materials, manufacturing process information and, in some cases, reliability data. Using a web-based interface, the user can create a morphological chart in just a few steps. First, the user specifies the artifacts to be used in the morphological search. Then, the number rows (sub-functions) and columns (solution alternatives per sub-function) are selected. Next, the user enters the sub-functions and the input/output flows for each. Once all the inputs are in, the search engine populates the morphological chart. Figure 13 shows an example of the output of the tool given the following functions: Import human energy, convert human energy into mechanical energy, transfer mechanical energy, and export mechanical energy (Design Engineering Lab | OSU, 2010).



Criteria	Artifacts							
Input Flow: human energy **Subfunction:** import **Output Flow:** human energy Search took: **0.993** seconds.	electric switch (22.3%)	housing (16.89%)	handle (12.84%)	lever (11.49%)	knob (8.11%)	cover (7.43%)	guiders (6.08%)	latch release (2.03%)
Input Flow: human energy **Subfunction:** convert **Output Flow:** mechanical Search took: **0.909** seconds.	lever (21.54%)	electric switch (12.31%)	housing (10.77%)	handle (10.77%)	guiders (6.15%)	cover (4.62%)	knob (4.62%)	actuator (3.08%)
Input Flow: mechanical **Subfunction:** transfer **Output Flow:** mechanical Search took: **1.005** seconds.	gear (20.56%)	shaft (13.28%)	link (8.57%)	support (4.07%)	housing (3.85%)	guiders (3.21%)	lever (2.78%)	blade (2.57%)
Input Flow: mechanical **Subfunction:** export **Output Flow:** mechanical Search took: **0.982** seconds.	fastener (7.95%)	support (7.95%)	unclassified (5.96%)	N/A supporter (4.54%)	housing (3.97%)	rotational coupler (3.97%)	screw (3.97%)	gear (3.31%)

Figure 13 – Morphological chart generated using OSU´s Morphological Chart Search tool (Design Engineering Lab | OSU, 2010)

Morphological matrices are a useful tool to generate multiple solution alternatives for complex design problems and to organize the information around these alternatives. Also, the functional decomposition process in this methodology allows pairing it with design repositories and knowledge databases. In spite of these benefits, there are some issues that the designer must address when using morphological charts. The first one is that the combination of design alternatives can generate a large number of concepts that might be unmanageable for the design team. The second issue is that morphological charts can generate infeasible concepts if the functions or the alternatives are coupled. To address these issues, a criterion to prune the large set of combinations is needed in order to extract a feasible alternative set that will become the input for the concept selection process.

2.2.2 Theory of Inventive Problem Solving (TRIZ)

The Theory of Inventive Problem Solving (TRIZ, per its Russian acronym) is an analogy method for problem solving initiated by a group of researchers led by Genrich S. Altshuller

(Barry, Domb, & Slocum, 2006). This research effort started in 1946 with the hypothesis that there are universal principles to solve problems that have been used in the most relevant innovations. Figure 14 describe TRIZ problem solving method: once the specific problem is defined, it is translated to a general problem. TRIZ research has developed techniques to synthesize general solutions to these problems. Then, this general solution is translated to a specific solution for the problem.

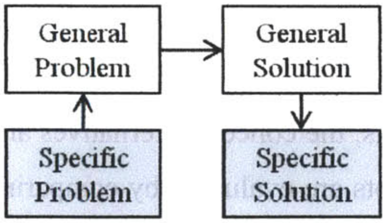


Figure 14 - TRIZ Problem solving method (Barry, Domb, & Slocum, 2006)

One of these techniques is the use of the *40 Principles of Problem Solving*. These principles were identified through more than 60 years of research, analyzing a large amount of patents and inventions. The TRIZ methodology acknowledges the existence of contradictions in design problems that should be eliminated. These contradictions are classified in two groups: technical and physical. Technical contradictions are also known as trade-offs or conflicts between two valuable parameters. Technical contradictions are related to the configuration of the system. Physical contradictions are conflicting requirements that are independent of the system configuration. TRIZ research has defined 40 principles to solve Technical contradictions and 4 that help solve the Physical ones. TRIZ is considered an analogy method because it generates solutions to design problems by looking into solutions that have solved similar problems in other domains.

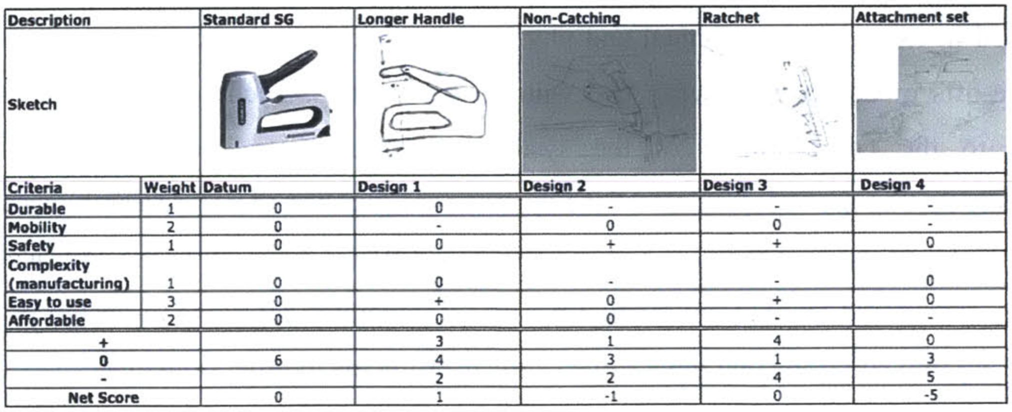
2.3 Frameworks for concept selection

2.3.1 The Pugh Method

Controlled Convergence or the Pugh Method was formalized by Stuart Pugh (1981) as a concept selection framework that became broadly used in mechanical design. Pugh's tool, the Decision Matrix has been applied in other methodologies such as Quality Function

Deployment (QFD). One of the objectives of this methodology is to minimize "conceptual vulnerability" in the design of the product. A concept is vulnerable (weak) when there is lack of thoroughness in the selection process and when a strong concept is selected but the reasons for its strength are unknown.

This method starts by defining the initial solution set using sketches developed at the same level of detail. Then, comparison criteria are selected (typically cascaded from the design requirements of the product). One of the concepts is selected as datum or baseline. Afterwards, the decision matrix is populated. In the first column, the decision criteria are listed. In the rest of the columns, the concept alternatives are displayed. Once the decision matrix is populated, the concepts are evaluated by comparing them with the datum. These evaluations are then recorded in the decision matrix. A "+" is assigned when the concept is better than the datum, a "-" is assigned when the concept is worse than the datum if no significant difference can be identified, an "S" or "0" is assigned. This evaluation is done for each concept-criterion combination. Figure 15 depicts an example of a Decision Matrix.



Description		Standard SG	Longer Handle	Non-Catching	Ratchet	Attachment set
Sketch						
Criteria	**Weight**	**Datum**	**Design 1**	**Design 2**	**Design 3**	**Design 4**
Durable	1	0	0	-	-	-
Mobility	2	0	-	0	0	-
Safety	1	0	0	+	+	0
Complexity (manufacturing)	1	0	0	-	-	0
Easy to use	3	0	+	0	+	0
Affordable	2	0	0	0	-	-
+			3	1	4	0
0		6	4	3	1	3
-			2	2	4	5
Net Score		0	1	-1	0	-5

Figure 15 – Decision matrix for staple gun concept alternatives (Staple gun redesign - DDWiki)

This process should be executed as a team activity (but moderated by a member of the team). The evaluations are product of through discussions among team members. Pugh's methodology allows some flexibility to make adjustments to the Decision Matrix when strong concepts do not arise, for example changing datum concept or removing common strengths. Once the evaluation is done, a score is computed by counting the number of "+",

"-" and "s" evaluations. The strongest concepts are then selected for further development (higher level of progression and detail). Once this is done, the matrix is updated and the process is rerun. These iterations are done several times until the concept is selected. Pugh (1981) suggests that five to six iterations are required to achieve a strong concept with solid foundations.

2.3.2 Set-Based Concurrent Engineering

Set-Based concurrent engineering is a design approach synthesized by Ward et al. (1999) from observations of the design processes used in the Japanese automotive industry, more specifically, at Toyota. In this research effort, Ward et al. acknowledge Toyota is faster and more efficient in developing product than its American competitors and decodes the practices behind this competitive advantage.

Ward et al. (1995) classify product development methods in point-based and set-based. In the point-based approach the team first proposes several solutions to address the design problem. These alternatives are evaluated and the process quickly converges to a single solution. Then, the team iterates over it in order to meet all the objectives. The analysis and feedback of the engineering groups to the design proposal occur in series and the feedback loops have a long delay. In contrast, the set-based approach considers a larger range of design alternatives during the initial stages in the process. This alternative set is progressed in parallel and is gradually narrowed by eliminating underperforming alternatives until the final concept is achieved. This design approach is also known as *The Second Toyota Paradox*: delay key decisions longer than in the point-based approach (Ward, Liker, & Cristiano, 1995).

Ward et Al (1999) deducted three principles to formalize the concept of Set-Based Concurrent Engineering: *Map design space, Integrate by intersection and Establish feasibility before commitment.* The first principle, *Map design space*, guides the process to characterize and document the design alternatives and feasible regions. The stakeholders involved formally determine the feasible region in the alternative set using multiple techniques: design checklists, surrogate test data, simulations, prototyping, etc. By studying multiple alternatives, the design team explores the design space and understands the trade-offs involved. Once defined, alternative sets and feasible regions are clearly communicated using design matrices, tradeoff curves and parameter intervals.

The second principle, *Integrate by Intersection*, outlines the way the system is integrated. First, the design team looks for intersections in the feasible regions of the stakeholders. By doing this, the alternative set converges to solutions that are feasible for all stakeholders and enables the team to find the best balance from a system perspective. Second, design teams apply the minimum constraint necessary to allow flexibility to make final changes to improve performance, balance the system or react to unexpected issues. The third element in this principle is fostering conceptual robustness. A concept is robust when all feasible regions are met regardless of pending decisions.

.

The third principle, *Establish Feasibility before Commitment*, encloses the idea of making sure the team explores all the alternatives and understands the tradeoffs involved before selecting a final solution. To do this, the alternative set is gradually reduced and design detail increases simultaneously. The decision making process is fundamental to ensure the design is completed within the project boundaries for time and resources. At Toyota, the decision making process is led by the chief engineer and senior management. A key element to ensure a successful project is discipline. All stakeholders must keep their parameter within the agreed alternative set. If any of the stakeholders violates the boundaries of the solution set, rework will occur as the change will be unexpected by the rest of the team. Toyota controls the concept selection process through project gateways and prototype builds. The pace for concept selection is determined by the complexity of the system to select and the associated lead times. A system with a long development time will be selected earlier than a system with lower level of complexity and lead time.

Chapter 3 - Conceptual design in an automotive OEM

This thesis proposes a concept development methodology for automotive Exterior Systems considering two objectives: maximization of the value to the stakeholders and reduction of the waste in downstream activities. To develop this methodology, the processes of a major automotive OEM were studied. To set the context for the proposed methodology, this chapter provides an introduction to Exterior Systems, automotive product development projects and the organizational structure at the OEM. Furthermore, this chapter reviews and analyzes the OEM's concept development process to develop Exterior Systems. This analysis allows identification of the problems the proposed methodology should address. For convenience, the acronym AOEM (Automotive Original Equipment Manufacturer) will be used to name the company under study.

To gather information, the author conducted multiple interviews and reviewed AOEM's process and project-specific documentation. In this effort, AOEM employees from different Product Development groups and organizational levels were interviewed. The interviews were recorded and transcribed for analysis. As an AOEM employee, the author had full access to process and project documents. To avoid disclosing confidential information and protect intellectual property, the author paraphrased the information obtained in the research and normalized numeric data.

3.1 Introduction to Exterior Systems development

3.1.1 Automotive system decomposition

Automotive products are complex systems with a large number of components and functions. To manage this complexity during the product development process, AOEM decomposes the vehicle into lower order systems. Understanding this decomposition is important as it is the foundation of the organizational structure. Table 1 shows the first order functional decomposition of the product used by AOEM. Each system in Table 1 can be further decomposed into subsystems and components. This partition helps organize both information and people. In addition to the functional decomposition, AOEM uses an attribute decomposition to manage several characteristics that emerge at the product level (vehicle) as a result of the interaction of assembled subsystems and components. Table 2 shows the first order attribute decomposition used by AOEM.

Table 1 - Functional vehicle decomposition used by AOEM (first order)

Vehicle systems		
1. Body systems	7. Transmission systems	13. Information and warning systems
2. Frame systems	8. Clutch systems	14. Electrical power supply systems
3. Engine systems	9. Exhaust Systems	15. In-vehicle entertainment systems
4. Suspension systems	10. Fuel Systems	16. Lighting systems
5. Driveline systems	11. Steering systems	17. Electrical distribution systems
6. Brake systems	12. Climate control systems	18. Electronic systems

Table 2 - Attribute vehicle decomposition used by AOEM

Vehicle attributes	
1. Appearance	7. Durability
2. Aerodynamics	8. Safety
3. Noise Vibration and Harshness (NVH)	9. Package
4. Thermal management	10. Fuel economy
5. Vehicle dynamics	11. Weight
6. Craftsmanship	

Exterior Systems

Exterior Systems, on which this thesis concentrates, are a group of second order systems derived from the decomposition shown in Table 1. These systems aggregate to form the exterior of the vehicle. Exterior systems cluster components with *A-surfaces* and components with purely functional purposes. As information, in the automotive argot, *A-surfaces* are those that the customer can see and touch. To illustrate this, Figure 16 shows a typical section of the interface between the roof and the windshield systems. In this example, the external surfaces of the *roof-outer-panel* (roof system component) and the *laminated glass* (windshield system) are considered *A-surfaces*. In contrast, components such as the *header panels* (roof system) and the *adhesive* (windshield system) provide the structural function.

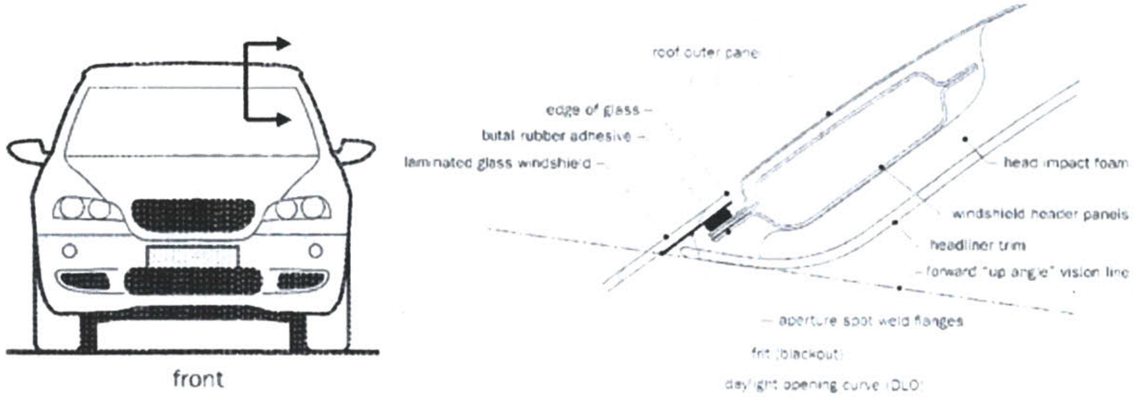


Figure 16 - Typical section roof system at windshield interface, modified from (Macy & Wardle, 2008)

Table 3 lists the groups of systems that are typically classified as Exterior Systems. The roof system shown in Figure 16 belongs to group A, *Body structure* systems. The windshield system is part of group F, *Glass systems*.

Table 3 - Vehicle Exterior Systems

Exterior systems	
A. Body structure systems	G. Lock and latch systems
B. Front end systems	H. Wiper systems
C. Closure systems	I. Roof opening panel systems
D. Exterior trim systems	J. Bumper systems
E. Mirror systems	K. Front lighting systems
F. Glass systems	L. Rear lighting systems

3.1.2 Automotive product development projects

Exterior Systems are designed in the context of automotive product development projects. The following pages provide an overview of these projects when configured using a *platform strategy*. Also, a classification of these projects from an Exterior Systems' perspective is presented.

The Platform Strategy

Most of the mainstream automotive OEMs develop their products using a *platform strategy* (de Weck and Suh, 2006). This involves creating product families that share a set of systems and parameters (a platform). Shared systems in the platform can be either communized components or component families (components with the same architecture but different execution of design variables). The benefit of this strategy is a more efficient use of the product development resources, reductions in development costs and accelerated time-to-market. Even though the elements of a platform are not the same among product families or automakers, it is noticeable that the platform systems are typically structural components that are not apparent to the customer. Figure 17 shows examples of body structure systems that are elements of a platform (Ford Focus, C1-Platform). Moreover, a vehicle platform not only involves shared systems but also shared parameters. Figure 18 shows the Volkswagen Golf wheelbase (distance between wheels), which is a shared parameter among vehicles in the VW group PQ35 platform: Audi A3, Seat Leon or Skoda Octavia.

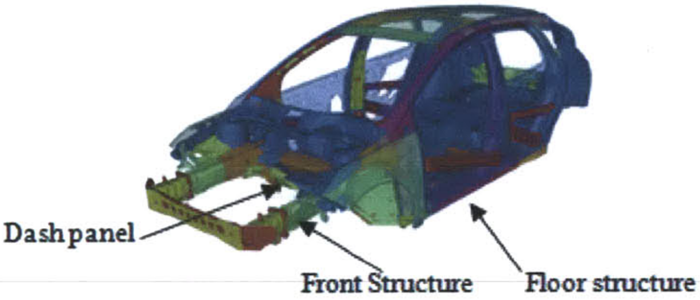


Figure 17 – Ford Focus body structure: platform parts, modified from (Autopress News, 2010)

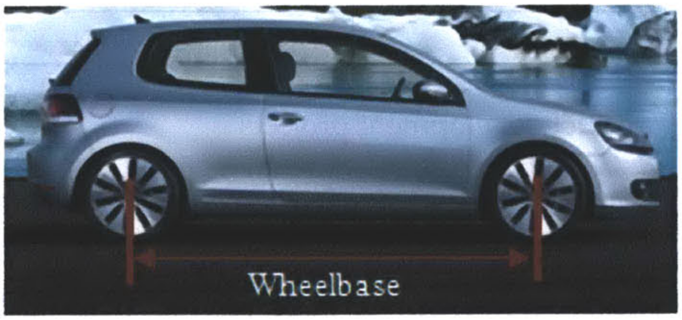


Figure 18 – 2009 Volkswagen Golf wheel base, modified from (Netcarshow.com)

In a *platform strategy*, the non-shared systems are the ones that are different among the products that share the platform. In the automotive context, these systems allow creation of products with different body styles and appearance within the platform. Most of the Exterior Systems listed in Table 3 can be classified as non-shared systems.

Classification of automotive PD projects

Automotive PD projects can be classified by the amount of work that the project involves. This workload is directly related to the number and the type of new components to be developed. From Exterior Systems' perspective, most automotive PD projects configured with a *platform* strategy can be classified in four categories: *Body & Platform Development*, *Platform Derivative*, *Mid-cycle Update* and *Product Derivative*. The following elaborates on these categories.

Body & Platform Development

These are the largest projects in this classification and involve an all-new exterior and a new or heavily modified platform. These projects imply development in all attributes (Table 2) and multiple levels of system integration. *Body & Platform development* projects allow major styling changes given that all the components that are visible to the customer are new. The styling and platform changes that occur in these projects affect the basic exterior dimensions of the vehicle such as the wheelbase, overall length, width, height, front and rear overhangs. In addition, these projects enable the development of multiple body styles within the same nameplate. For example, a car nameplate can accommodate a sedan, a hatchback and a wagon.

Figure 19 shows an example of a *Body & Platform development* project, the 2003 Audi A3. The left side of the figure shows the 2002 model-year (MY) A3 that used the PQ34 platform of the Volkswagen Group. For the 2003MY, the A3 (right) experienced a noticeable styling change and migrated to the PQ35 platform. As a result, exterior sheet metal panels, day light openings (windows), lighting systems, fascias, ornaments and wheels are new. The 2003MY A3 was the first vehicle that used the PQ35 platform to hit the marketplace, therefore in this project the development of the product and the platform was coupled.

Figure 19 – Body & platform development example: 2003 Audi A3[4]

Platform Derivative

A *Platform Derivative* is a project that involves an all-new exterior and minor changes to the platform systems. In these projects, design teams use platform systems that are at an advanced stage of development or are already in production. Therefore, platform systems remain substantially unchanged as result of the new vehicle. *Platform Derivative* projects use platform systems to create products with similar dimensions but different styling, thereby targeting different customers. These projects require full development in all attributes and in non-platform systems. *Platform Derivative* projects allow creation of multiple body styles within the same nameplate, different brand vehicles or different vehicle categories.

Figure 20 shows an example of a *Platform Derivative* product, the 2006MY Dodge Charger (right). This vehicle used the LX platform that was first launched in the 2005MY Chrysler 300 (left). All-new exterior systems allowed the differentiation required to execute the styling of a different brand (Dodge vs. Chrysler). Figure 21 shows another example of *Platform Derivatives*: 2006MY Ford Fusion (center) and the 2007MY Ford Edge (right). These vehicles used the CD3 platform first used in the Mazda 6 (left). The Ford Edge is an example of a *Platform Derivative* that was developed for a different product category than the platform donor.

---

[4] Vehicle images obtained from public websites: www.wikipedia.org / www.necarshow.com

Figure 20 – Platform derivative example: 2006 Dodge Charger [5]

Figure 21 – Platform Derivative example: 2006 Ford Fusion and 2007 Ford Edge (CD3 platform)[6]

Mid-cycle Update

These projects are done to update products that are already in the market in order to keep its styling up-to-date in the eyes of the customers. *Mid-cycle update* projects involve changes in some of the exterior systems but maintain most of the structures. Typically, changes are concentrated in the front of the vehicle, the rear and the wheels. In some cases, however, the door panels might also be affected. A key difference relative to the first two project categories is that the profile of the roof does not change relative to its predecessor. This enables the team to keep the size of the pillars and the DLOs, therefore, reducing attribute development.

Figure 22 shows an example of a *Mid-cycle update*, the 2010 Ford Fusion (right). This project involved changes in the front (hood, front fascia, grille, head-lights), rear (tail lamps, deck-lid, rear fascia), ornaments and wheels.

---

[5] Vehicle images obtained from public websites: www.wikipedia.org / www.necarshow.com

[6] Vehicle images obtained from public websites: www.wikipedia.org / www.necarshow.com

Figure 22 – Mid-cycle update example: 2010 Ford Fusion[7]

Product Derivative

Product Derivatives are those projects configured to create a special edition of a nameplate. The changes in exterior are limited to the front and rear of the vehicle, in order to achieve some level of differentiation relative to the base line model. The difference between a *Product Derivative* and a *Mid-cycle update* project is that in the former, the new vehicle will share the showroom with the base-line model and retains the styling concept. Figure 23 shows an example of a *Product Derivative*, the 2009MY Ford Focus RS (right). In this product, the exterior design team changed fenders, front/rear fascias, the rear spoiler and rocker moldings relative to the baseline, the 3-door Ford Focus (left).

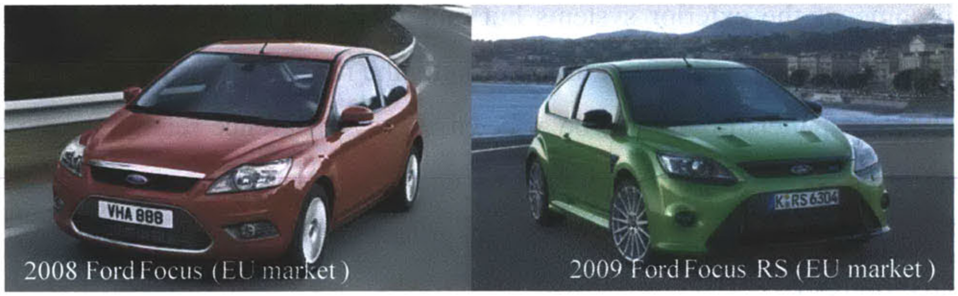


Figure 23 – Product derivative example: 2009 Ford Focus RS[8]

The project classification described above is relevant to the methodology proposed in this thesis as it is used to define the system boundaries of the concept.

PD projects at AOEM

---

[7] Vehicle images obtained from public websites: www.wikipedia.org / www.necarshow.com

[8] Vehicle images obtained from public websites: www.wikipedia.org / www.necarshow.com

To develop its future product portfolio, AOEM configures a set of product development projects through a cyclic planning process. These projects are internally called *programs* and are configured when the target market, the set of assumptions, project objectives and resources are defined. Project objectives include product content, target costs, production volumes and time-to-market. The assumptions are information elements that "back-up" the project objectives; for example, the mix of new, legacy and platform parts. AOEM uses a structured and explicit Product Development Process (PDP) as a framework to conduct the programs. This PDP formalizes several program milestones as well as the processes and deliverables that should be completed for each gateway. This standardized process is applied to every PD project in the company.

AOEM uses a *platform strategy* to develop its products. It allocates resources and defines the timeline according to the program size. AOEM defines program size by the amount of change in the product relative to a baseline. This reference is usually the previous model of the product or another product in the same platform (if the product to develop is a new entry).

3.1.3 Organizational structure at AOEM

The organizational structure used by the Product Development division of AOEM is a form of *matrix* organization (Allen, 1977). This structure has two main branches: Program Management and Specialty Departments. The former branch is configured around vehicle projects and is responsible for task completion (PDP deliverables), fulfillment of project objectives and project integration. The second branch, Specialty departments, cluster professionals with common technical expertise and is aligned with the functional and attribute decompositions mentioned in 1.1.1. Consequently, this branch of the structure can be divided in two: system and attribute departments.

Most of the personnel without a managerial position belongs to a Specialty Department and is assigned to one or more programs. In this situation, engineers report to a department manager and to a program manager. But, the type of power relationship is different in each case. Department managers control the allocation of engineers to the programs, define the annual individual objectives and conduct the performance reviews. Also, department managers shepherd the technical aspect of the system or attribute through design reviews. On the other hand, the Program Managers own the content of the product, the timing of the project and are responsible for capital resources. Therefore, the system and attribute engineers in the project report design progress, status of PDP deliverables and costs to the Program Managers. Moreover, engineers seek the program's team approval when a change in content or assumptions is proposed.

Program Managers report to Chief Engineers ("heavy-weight" project managers) who are the management heads of the programs. These individuals are system and project integrators as well as decision makers. Chief Engineers have a group of people supporting project related efforts: the program staff. The responsibilities of this group include the coordination of decision making forums and the maintenance of official program documentation. These documents include project timing, decision forum minutes, product content and program assumptions. In addition, the program staff also helps the team in deliverable execution. In these cross-functional activities, the program staff manages the interaction between the product development team and other divisions in the company such as finance, marketing and manufacturing.

To illustrate how the matrix organization works at AOEM, Figure 24 depicts a fragment of the organizational structure. In this example, the system engineer S_{113} and the attribute engineer T_{213} are assigned to Project A. The system engineer reports to supervisor C_{11} and Manager M_1 in a system engineering department. Similarly, the attribute engineer reports to supervisor R_{21} and manager A_2 in the attribute engineering department. On the program side, both engineers report to the Chief engineer P_A.

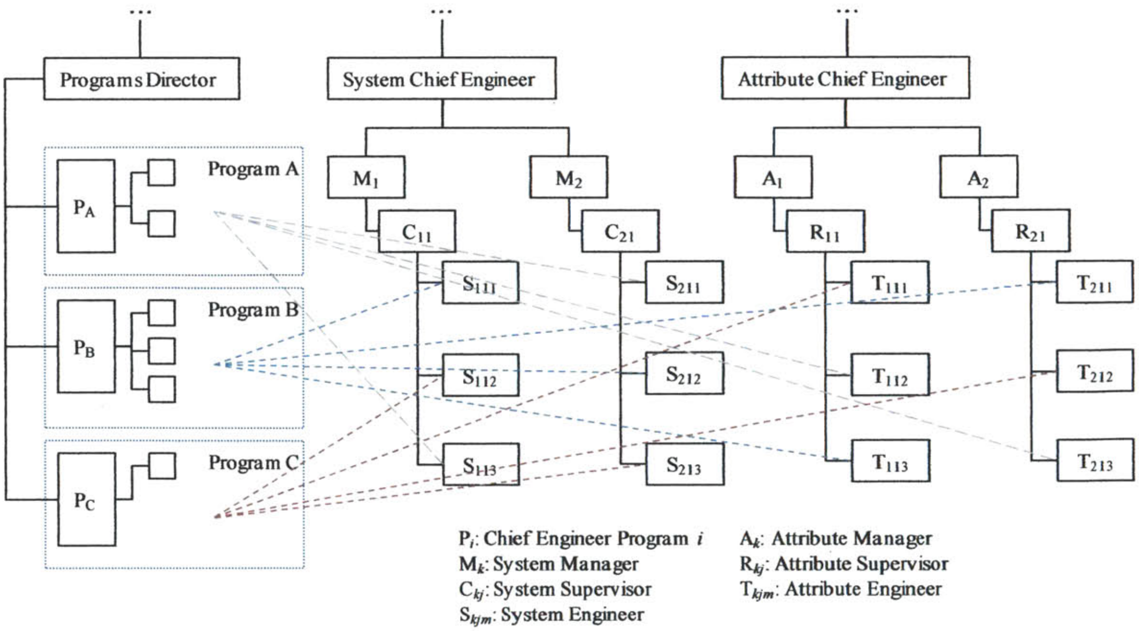


Figure 24 - AOEM matrix organization, template from (Allen, 1977)

Organizational structure plays a major role in the dynamics of decision making which is critical for concept selection. The Concept Development methodology proposed in this thesis is configured assuming a matrix organization and requires a system and project integrator figure such as a program Chief Engineer.

3.2 Exterior Systems conceptual design

The processes used at AOEM to conceptualize Exterior Systems are shown in Figure 25. First, in the *Elicit Value* process, the team identifies the needs of the stakeholders and defines value in the context of the product to be developed. The result of this process is a set of articulated goals and requirements that the systems under development should address. This set is used during the *Concept Development* process to generate and select concepts. Among these, Exterior Systems concepts are characterized as having a *Styling* and a Functional aspect. Both aspects are matured through interdependent sub-processes. The output of the *Concept Development* process is the system-level architecture. The architecture of the system is matured and optimized in downstream processes.

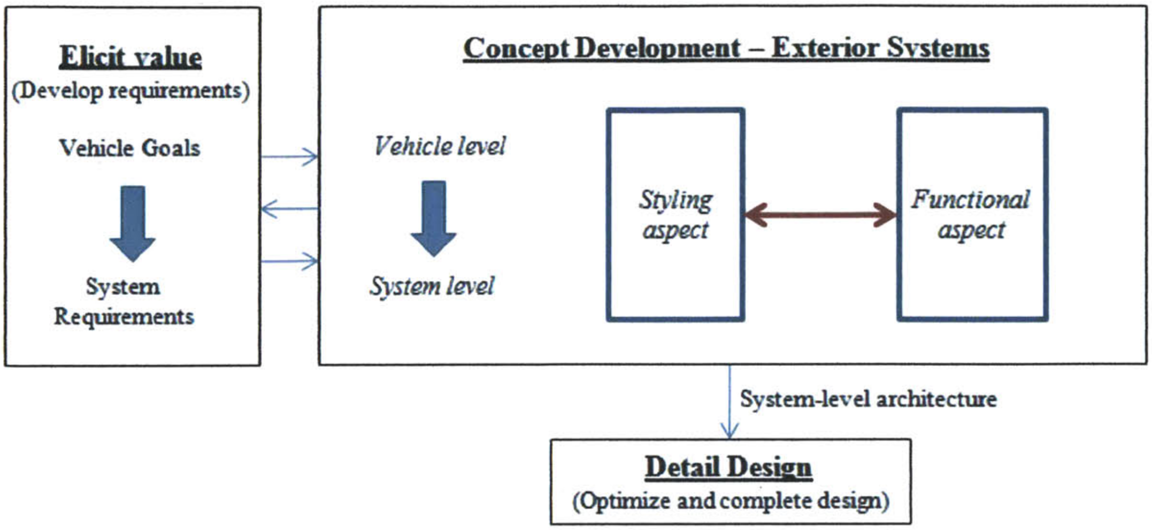


Figure 25 - Conceptual design process used at AOEM to develop Exterior Systems

3.2.1 Eliciting value of Exterior Systems

Value is an abstract concept that has multiple definitions in different knowledge domains. In the Systems Engineering domain, Ross and Rhodes (2008) define value as "relative worth, utility or importance, the quality of a thing considered in respect to its power and validity for a specified purpose or effect". Value is perceived and qualified by the stakeholders (including the customer) in multiple dimensions or elements. The elements of value in the system are those characteristics that can be measured or compared to evaluate the "goodness" of a system. In order to meet the demands of the stakeholders, a performance level in each value element is identified as a system goal/objective. Complex systems such as automotive exterior systems have multiple stakeholders and perceptions of value, therefore, multiple goals.

As described by Bartolomei (2007), the stakeholders of a system are the human elements (individuals or organizations) that affect or are affected by the system. The stakeholders can be internal or external to the system boundaries and define the performance level required in each dimension of value. Figure 26 lists the internal and external stakeholders of automotive exterior systems.

Stakeholders [Automotive Exterior Systems]	External	• Target customers • Regulators • Organizations in the automotive ecosystem • Dealer organizations
	Internal	• Studio • Marketing • System Engineering Groups • Attribute Engineering Groups • Purchasing • Finance • Service Engineering • Manufacturing Engineering • Program Chief Engineer

Figure 26 - Stakeholders, Automotive Exterior Systems

External Stakeholders

Meeting or exceeding the needs of the external stakeholders is critical to the success of the product in the market place. Unfortunately, these needs are often not clearly articulated or known. This situation becomes an issue to the product development team. In many cases, special methods must be used to extract and interpret this information. Another issue is the limited access the design team has to these stakeholders. This diminishes the ability of the team to acknowledge changes in stakeholder preferences or to clarify their needs. The external stakeholders of automotive exterior systems are classified in four groups: *Target Customers*, *Regulators*, *Dealers and Non-manufacturing Automotive Organizations*.

The *Target Customers* are those consumers with specific psychographic characteristics who are representative of the portion of the market to be addressed by the product. These stakeholders do not formally articulate their needs by themselves. Instead, focus groups, clinics and other tools are used to identify and formalize these needs. *Regulators* are usually government organizations that establish the rules in the marketplace. These needs are clearly articulated in the form of laws and regulations. An example of this type of stakeholder is the National Highway Traffic Safety Administration (NHTSA), a regulation entity for the US automotive market.

Dealers are the business partners of the OEMs that distribute the vehicles in the market. These entities own the showrooms and have direct contact with retail and fleet customers. As any business organization, these stakeholders seek profit from their operations. AOEM

Dealers articulate their needs through the *Dealer council*, an entity that interfaces with the manufacturer.

Other relevant stakeholders are the *Non-manufacturing Automotive Organizations*. This group involves multiple organizations in the automotive ecosystem with different objectives. These stakeholders have influence over Exterior Systems in multiple ways. Three types of organizations are considered in this category: organizations that configure industry standards, organizations that evaluate automotive products and organizations that synthesize customer preferences. Industry standards are a set of parameters agreed to by multiple manufacturers in an effort to homogenize methods, categories and designs that will facilitate business and product development activities across the industry. An example of an organization configuring industry standards is the Society of Automotive Engineers (SAE), which recently created the standard SAE J1772. This standard homogenizes the dimensional requirements for the charging ports, cords, and couplers to be used in electric and plug-in hybrid vehicles in North America (Society of Automotive Engineers , 2010).

Several OEM-independent organizations evaluate automotive products and communicate these results to the public. These stakeholders have had a significant effect in the system requirements due to their influence with customers. In order to get a positive review/rating from these organizations, manufacturers have implemented requirements to succeed in these third-party evaluations. The Insurance Institute for Highway Safety (IIHS) is an example. IIHS is a non-profit organization funded by auto insurers that tests and rates vehicles sold in the US for crashworthiness and vehicle damage in low speed collisions. IIHS awards the "Top safety pick" to vehicles with good performance in all crashworthiness tests (IIHS, 2010). This distinction is often used by manufacturers to market their products. Therefore, it has become part of the set of needs related ot the Exterior Systems of the vehicle.

Other important organizations in the automotive environment are ones that synthesize customer opinion and ownership experience about automotive products and communicate this information to other customers. An example of this type of organization is J.D. Power and Associates, a global marketing information firm that conducts surveys of quality and customer satisfaction. J.D. Power publishes its automotive studies and awards the top performers on an annual basis. Some of these studies are: Initial Quality, APEAL (Automotive Performance, Execution and Layout) and Vehicle Dependability (J. D. Power, 2010). As a result of the influence of these studies in consumer preferences, manufacturers like AOEM consider these evaluations in its process to elicit value.

Internal Stakeholders

The stakeholders that are internal to system boundaries play an active role in articulating value and decision making. These internal stakeholders are responsible for identifying and interpreting the needs of external stakeholders. Using this information, internal stakeholders translate external needs into system goals and requirements. Once these are defined, internal stakeholders assure that goals are met and they participate in trade off discussions when there are conflicts.

System Engineering Groups

This stakeholder classification refers to the engineering groups responsible for the systems listed in Table 1. These stakeholders formally articulate system objectives for functionality and quality. System Engineering groups are also responsible for integrating the requirements of the other stakeholders into their system. Suppliers that are contracted to develop systems and components are also included in this category. Although suppliers are not part of AOEM, they are considered internal stakeholders and part of the design team. They report to AOEM Engineering management given the contractual relationship.

Attribute Engineering Groups

The engineering groups in this category are responsible for the vehicle attributes listed in Table 2. This responsibility includes the definition of vehicle goals related to their attribute and the strategy to be deployed in lower order systems to achieve the vehicle objective. For example, the Safety Engineering group would be responsible for defining a target for the Euro NCAP[9] safety rating if the new vehicle is to be sold in the European Community. The

---

[9] European New Car Assessment Programme

safety engineers also have to delineate the means to achieve the proposed Euro NCAP target and work with the other stakeholders to implement these means.

Purchasing

The Purchasing group is responsible for the procurement of materials and services for AOEM operations, including vehicle components and engineering services. These stakeholders select suppliers, negotiate commodity pricing and manage commercial relationships with suppliers. The Purchasing department is interested in reducing the price of commodities, improving the quality of the purchased goods/services and business sustainability. In order to address these interests, Purchasing has teamed with the System Engineering groups to develop a commodity strategy. This strategy considers pricing, technology evolution and quality.

Finance

These stakeholders manage the monetary resources of the program. This group is interested in maximizing the Return of Investment (ROI) by reducing costs and maximizing revenue. The Finance department also estimates the cost of purchased commodities. These estimates are used to set price targets. Moreover, it is typical that elements of the Finance group join the program team to manage the investment of the project and to conduct financial studies.

Manufacturing Engineering

These stakeholders are responsible for design of the vehicle manufacturing and assembly processes. This engineering group defines the set of requirements that the system must meet in order to be manufactured within the means available to the team. This category also includes the supplier's manufacturing engineering groups.

Service Engineering

The Service group is responsible for defining the operations to maintain the systems of the vehicle throughout the lifecycle of the product. This group develops system requirements that enable maintenance operations.

Studio

These stakeholders develop the appearance/styling attribute of the product. Studio is responsible for articulating styling-related system requirements, developing the styling concept and assessing the goodness of the appearance of the vehicle throughout the project.

Chief Engineer

The Chief Engineer the head of the program team and is responsible for the vehicle as a system and as a project. This individual is the top level system integrator of the vehicle and a major decision maker. In this role, the Chief Engineer is responsible for resolving trade-off conflicts between goals and requirements.

Translating stakeholder needs into system requirements and targets

The process to identify and articulate the needs of the stakeholders starts before the product development project is formalized. A market opportunity is identified by senior executives as a result of the analysis of market data, trends and the corporate strategy. A small team is established to conduct advanced studies to develop high level assumptions to set up a program. As a result of these studies, the team articulates the stakeholder needs in terms of vehicle class, high-level vehicle architecture (platform selection) and qualitative targets for vehicle attributes. To enable the target setting process, the stakeholders define a set of competitive vehicles (market segment competitors + selected benchmark vehicles). Qualitative targets elicit the desired attribute performance level in comparison with the products in the competitive set. For example, a qualitative target for the *Package* attribute could be: “To be leader in *Occupant Roominess*”.

Attribute engineering groups are responsible for translating the qualitative targets into quantitative objectives. To do this, the products in the competitive set are evaluated to define the range in the performance metric that corresponds to the qualitative target. Then, transfer functions are used to define a numeric target. In addition to the attribute requirements, there are system-specific requirements. These are defined by the system engineering groups to ensure adequate system functionality, failure mode prevention and legal compliance.

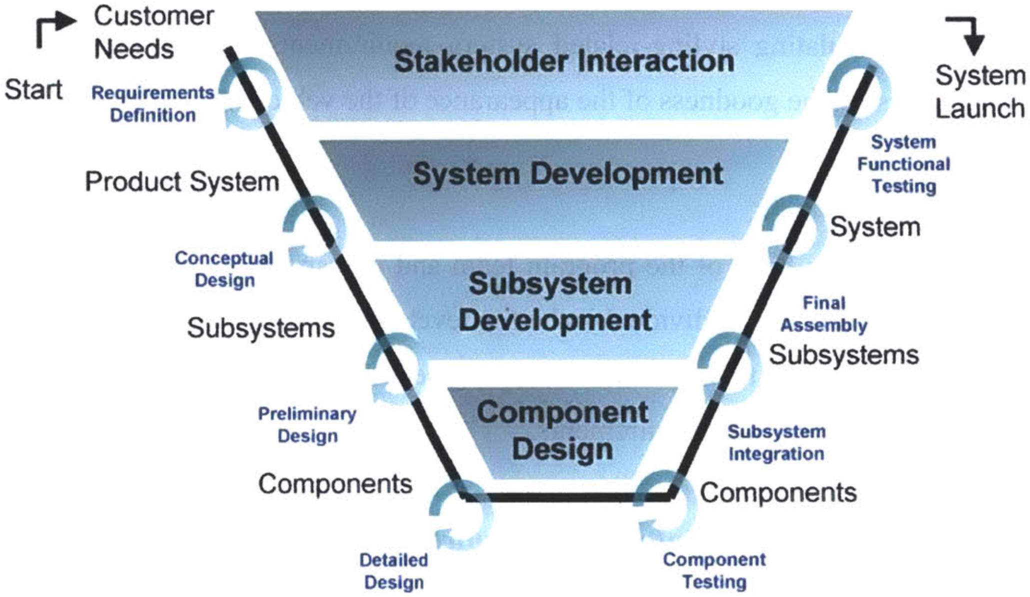


Figure 27 – The Systems Engineering V-model (MIT, 2008)

Both attribute and system requirements are decomposed and transferred to lower order systems using the Systems Engineering V-model (Figure 27). On the left side of the V, the stakeholders' needs are elicited at the highest level system (the vehicle). The requirements are gradually decomposed and deployed to lower order systems until the component level is reached. Inversely, on the right side of the V testing and validation processes are conducted bottom-up, starting at the component level and concluding at vehicle level. Multiple tools and methodologies are being used at AOEM to translate vehicle-level goals into system requirements. The House of Quality (QFD), DCOV (Design for Six Sigma) and other proprietary tools are used to this purpose.

To illustrate how requirements are transferred from vehicle level to lower-order systems we can use a *Package* attribute example. *Space & Size* is the *Package* sub-attribute related to occupant roominess. The *Space & Size* sub-attribute can be further decomposed in lower order characteristics. Package dimensions are at the lowest level in this decomposition. For this example, let's consider the package dimension *Effective Headroom* which contributes to the *1st row roominess* characteristic (space for driver and 1st row passenger). The goal setting process starts with the definition of a qualitative target for the *Space & Size* sub-attribute. Assume the goal established by the stakeholders is to "To be competitive". To translate this qualitative goal into measurable items, the *Package* team defines a transfer function that relates dimensions like *Effective Headroom* with the higher level characteristics. *Package* engineers conduct benchmarking studies to gather dimensional data of the vehicles in the competitive set. Competitor's dimensions and the transfer functions are used to define a target range for each package dimension. In this example, a "Competitive" target for *Space & Size* is translated into a "Competitive" target for *1st Row roominess* and *Effective Headroom.* The benchmarking analysis is used to define a lower and an upper numeric boundary for a "Competitive" *Effective Headroom* dimension. This range becomes a numeric target (minimum *Effective Headroom*) as design progresses. This target translates to a vertical position requirement for the headliner and the roof system. The example above shows how a vehicle attribute goal is translated into a system-level requirement.

Articulating value for the Appearance/Styling attribute

Due to its subjective nature, the process to articulate value from the appearance/styling attribute perspective is partially different. As described by an AOEM Studio Designer, the main goal of the vehicle styling is to evoke emotion and appeal to customers. The intent is to establish a stronger emotional connection with buyers than the competition in an effort to get their preference. Similar to other attributes, a qualitative goal is defined by the stakeholders (e.g. "To be leader in exterior appearance"). To translate this goal into parameters that can be evaluated or compared, Subject Matter Experts (SMEs) do detailed benchmarking studies to define comparator products that will be used to assess several styling characteristics. *Vehicle Proportions*, *Material Execution* and *Interface quality* are the characteristics considered in these studies.

The term *Vehicle Proportions,* refers to the distribution of volume in the vehicle. *Proportions* are critical in communicating the purpose and type of vehicle. This styling characteristic is affected by the position of the major volumes in the vehicle: the power-plant, the occupants, its cargo and the wheels. Even though the goodness in the

Proportions of a vehicle is subjectively evaluated, these can be measured and compared using ratios between exterior dimensions. Some of these dimensions are: wheelbase, front/rear overhangs, track width, overall length, height and tire outer diameter.

Material Execution is the combination of materials and finishes used on the A-surfaces of exterior and interior components. A "good" material execution is "harmonious" and "tasteful" as judged by Studio stakeholders.

Interface quality refers to the apparent assembly quality in the components that a customer can see and touch. Textures, paint quality, size and evenness in the gaps between body panels are some of the elements that contribute to this quality perception.

The performance level relative to these styling characteristics is subjectively evaluated. The benchmarks identified in this process are used to assess the goodness of the systems under development (by comparison). Another important element in the set of appearance/styling requirements is Design DNA. An AOEM Studio Designer describes it as "personality, the statement the vehicle or brand is making to the consumer". It can be related to a whole brand or to a specific model. A brand's Design DNA contributes toward differentiation of the brand's products in the market place. The elements of the DNA should augment or reinforce the brand's value proposition. DNA can be chosen by stakeholders but sometimes it is already there as part of the heritage of the product. Iconic vehicles such as the Ford Mustang or the Volkswagen Beetle have their own DNA: design features that constitute the identity of the product along its history.

The elements of Design DNA are *Surface Language* and *Graphic Language*. The first term refers to the features of form in the *A-surfaces* such as character lines, surface curvature transitions and radii size. The second term, *Graphic Language* refers to the shapes used in the *A-surfaces* of components, for example headlight profiles or grille motives.

Studio stakeholders communicate their preferences and requirements through imagery, *A-surfaces* and material samples. As stated earlier, the term *A-surface* is assigned to the surfaces of interior/exterior body components that the customer can see and touch (considering all closures in closed position). A group within the Studio organization creates CAD[10] representations of these surfaces that are shared with the team. Studio uses CAD data and imagery to articulate size and shape requirements for Exterior and Interior systems. Material samples are used to articulate material and finish requirements.

Maturing System Requirements

The *Elicit Value* process articulates the goals and requirements of the product and its systems. As described in this chapter, this process starts at vehicle level and gradually progresses towards lower-order systems. In this course of action, requirements gain definition and uncertainty is reduced. To do this, the *Elicit Value* process requires feedback from the *Concept Development* process. The latter process uncovers conflicts among targets and seeks for the feasible boundaries of the system. The *Concept Development* process help solve compatibility issues and removes uncertainty from the system. At the end of the *Elicit Value* process, articulated system requirements must be compatible and feasible.

Classification of system requirements

Articulated system-level requirements that result from the *Elicit Value* process can be classified in the following categories:

- Performance within boundaries. In this type of requirement, lower and/or upper boundaries are defined for the performance metric. Lower boundaries define the minimum acceptable performance and upper boundaries define the maximum acceptable condition.
- Discrete requirements. This category refers to the requirements that cannot be measured using continuous metrics, for example, the availability of a feature (available / not available).
- Geometric Targets. In this category the requirements are set as geometric targets to match. The closer the system geometry is to the target the better. Studio's *A-surface*

---

[10] CAD: Computer Aided Design

is an example of a geometric target. A design that matches the *A-surface* proposed is more valuable to the Studio's stakeholders than one that deviates from it.

3.2.2 The Concept Development process

Similar to the process *Elicit Value*, the *Concept Development* process starts at vehicle level and progresses towards lower-order systems. Figure 28 presents AOEM's processes to conceptualize Exterior Systems, showing more detail in the *Concept Development* process. The *Concept Development* process can be decomposed into four interrelated sub-processes, which are arranged in two columns. The sub-processes in the left column develop the *Styling* aspect of the concept; the ones in the right develop the *Functional* aspect. The following pages describe with more detail how these sub-processes interact to configure the system architecture, the output of the process. The methodology proposed in this thesis, addresses the *System Conceptualization* sub-process.

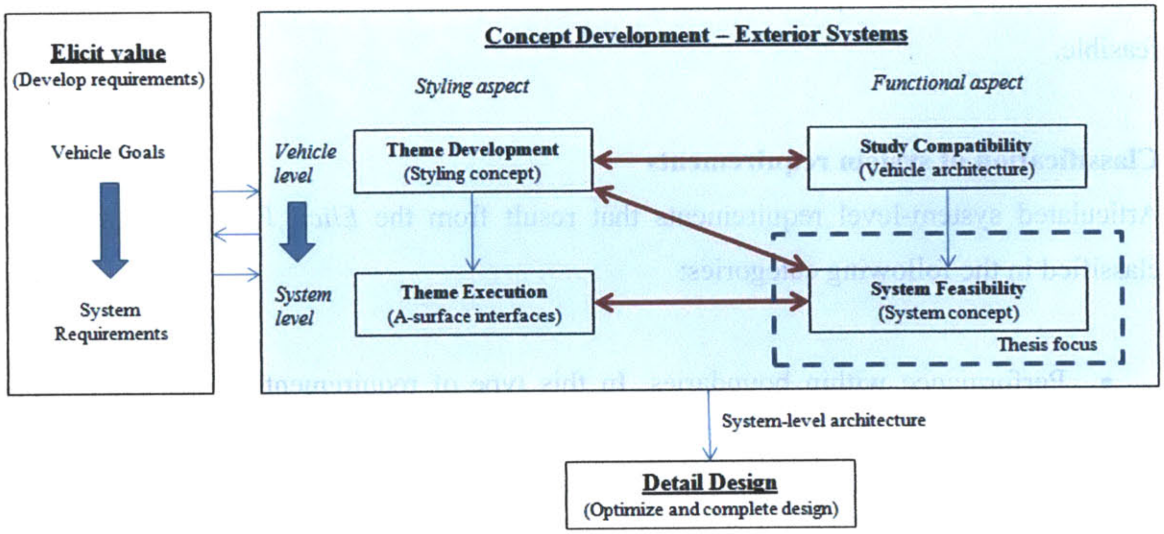


Figure 28 - Conceptual design process for Exterior Systems

At AOEM, the *Concept Development* process to develop Exterior Systems starts with the definition of the vehicle-level concept. In this thesis the vehicle-level concept is considered "defined" when the styling *Theme* and the platform systems are selected and the team knows which systems have to be developed. The *Theme* is the styling concept of the vehicle. It can be described as a set of elements of form that are built into the product with the intent of conveying an idea and evoking emotion in the observer. These elements of form are the proportions of the vehicle, the surface treatment and the graphics.

The development of the vehicle level concept starts with the interaction of *Theme Development* and *Study Compatibility* sub-processes. *Theme Development* is a complex creative process conducted by Studio stakeholders that involves the generation of multiple styling concepts followed by a gradual concept selection. On the other hand, the *Study Compatibility* sub-process involves conducting studies to define a vehicle architecture that is compatible with the goals of the product and the *Theme*.

Theme Development starts once Studio receives a set of project assumptions from the Program Team and the Marketing group. This information includes product content (features), financial assumptions and a description of the design needs of the target customer. In order to get additional insight about the Design needs of the target customer and industry trends, Studio conducts research.

During the research process, the Studio team collects imagery of objects that represent the preferences of the target customer such as chairs, watches, shoes, etc. This set of images is discussed with Marketing stakeholders to identify the range of acceptable styling (styling bandwidth). Studio Designers use these images and Design DNA needs as stimuli for creating multiple appearance concepts in the form of sketches. According to a Design Manager at AOEM, this is the artistic part of the process and is critical for creating a passionate, emotional connection with the customer. Sketches and images with a common styling idea are clustered. Each of these clusters will mature into a *Theme*.

Vehicle proportions are the first element to develop in the *Theme*. As described earlier in this chapter, proportions are design needs established by Studio stakeholders through benchmarking. The design space for this characteristic is delimited by the capabilities of the platform and the architecture of the vehicle. To define the proportions of the *Theme*, feedback is required from the *Study Compatibility* sub-process.

During the *Study Compatibility* sub-process, a small group of attribute and system engineers assess the consistency of platform systems, program assumptions and stakeholder needs. Among these studies, the team evaluates Studio's wants for vehicle proportions. Therefore, *Theme Development* and *Study Compatibility* are coupled sub-processes. Furthermore, *Study Compatibility* helps the program team select the platform systems to use in the product and helps refine assumptions for the new systems under development.

Once the proportions and the vehicle architecture are compatible, Studio develops the surface treatment and the graphic elements in the *Themes*. As the styling concepts mature, there is increase in detail. To guide this styling concept evolution, the *Theme Development* sub-process requires input from senior Studio stakeholders, market research and the *System Feasibility* sub-process. At the same time the *Themes* progress, concept selection occurs. Studio, Marketing and Program stakeholders gradually discard the less promising *Themes* until one is selected. At the end of the *Theme Development* process, the styling concept should be compatible with the architecture of the vehicle and with the program assumptions. In addition, the styling concept should have been successful in the market research.

Once the *Theme* is selected, the *Theme Execution* sub-process begins. In this sub-process, Studio stakeholders implement their component interface requirements in the *A-surfaces*. These requirements include component size/position, interface gap size and surface flushness. Also, during *Theme Execution,* Studio evaluates the compliance of the Theme to the goals elicited by the stakeholders in terms of *Interface quality* and *Material Execution. Theme Execution* is an iterative process that is coupled with *System Feasibility.* First, Studio divides the vehicle into multiple surfaces representing components. The feasibility of these interfaces is assessed by attribute and system engineering groups and feedback is provided to Studio. During this iterative process, the team configures feasible solutions to execute the *Theme*.

The *System Feasibility* sub-process develops the functional aspect of the concept at system level. The purpose of this sub-process is to define the system architecture. In this thesis the system architecture of an Exterior System is considered "defined" when: technology is selected, system decomposition is articulated, system functions are defined and there is compatibility between the system-level requirements and the system architecture. *System Feasibility* starts before the *Theme* is selected. In the first part of this sub-process, system engineering groups study the program assumptions for their systems and conduct benchmarking studies using the competitive set. In addition, system engineers receive input from Purchasing, Finance and Core-engineering groups[11] related to the commodity and technology strategies. Using this information, system engineers develop a set of concepts that is communicated to the team. The level of definition in these concept sets is limited to major system architecture elements such as technology, functionality and show preliminary system decomposition. This information is useful to estimate system costs, to refine project assumptions and to provide helpful input for *Theme* progression. In this part of the process, *System Feasibility* is coupled with *Theme Development*.

These functional concept sets are communicated to the rest of the team in the form of decision matrices that include an initial performance assessment relative to attribute requirements, cost and weight. These decision matrices are discussed by internal stakeholders in multiple decision making forums in order to select one concept. In this context, functional concept selection implies choosing a set of technologies to achieve the functions of the system, a set of materials and preliminary system decomposition. This concept selection does not happen simultaneously for all systems; "major" systems are selected first. It is important to emphasize that after functional concept selection, there is still a significant amount of work to do to fully define the system architecture. After the functional concept is selected, the system engineering groups iterate over the same concept to define the system architecture.

---

[11] Core-engineering groups are specialized system engineers whose responsibilities include defining cross-vehicle system requirements and technology strategy.

To progress the system-level concept towards system architecture definition, *System Feasibility* requires interaction with *Theme Execution,* leading to multiple iterations. As part of this interaction, the *Theme* and the system architecture converge to a feasible solution that should meet all system requirements (including Studio's).

3.3 AOEM Concept Development process analysis

The purpose of this thesis is to develop a Concept Development methodology that enhances the value delivered to the stakeholders while reducing waste in downstream activities. To achieve the thesis goals, the problems that constrain value and generate waste in the baseline process must be understood. In this research, three systemic problems were identified in AOEM's Concept Development process: 1) *The functional aspect of the concept converges too quickly*, 2) *Uncertainty is not recognized case by case* and 3) *System to system interaction is not considered in concept selection.*

3.3.1 The functional aspect of the concept converges too quickly

As explained in 3.2.2 the Concept Development of Exterior Systems involves the progression of two aspects of the concept: styling and function. To develop the styling concept, Studio stakeholders create multiple *Themes*, configuring an alternative set. As the detail in the set progresses, the number of alternatives considered in the set is gradually reduced until one concept is selected. In a similar way, the System Engineering groups consider multiple alternatives to configure the functional aspect of the concept. The key difference is that the alternative set of the System Engineering groups converges much faster than that of the Studio group. This timing difference reduces the ability of the team to achieve optimal solutions and opens the possibility for rework downstream in the process.

Figure 29 shows a comparison over time of *Theme* selection and functional concept selection, considering the standard process in a program that involves an all-new exterior. The horizontal axis displays eight development gateways. At each gateway, the internal stakeholders have a formal review of the status of the program to evaluate if the deliverables were achieved in order to move to the next gateway. System-level architecture for all Exterior Systems must be fully defined at C8. The line in blue shows the gradual concept selection of the *Theme*. The styling concept is selected at C5. The line in red shows the cumulative percentage of Exterior Systems with concepts selected. 100% of the Exterior Systems have its concepts selected at C5. The green "stars" represent points in time were the team receives input from market research.

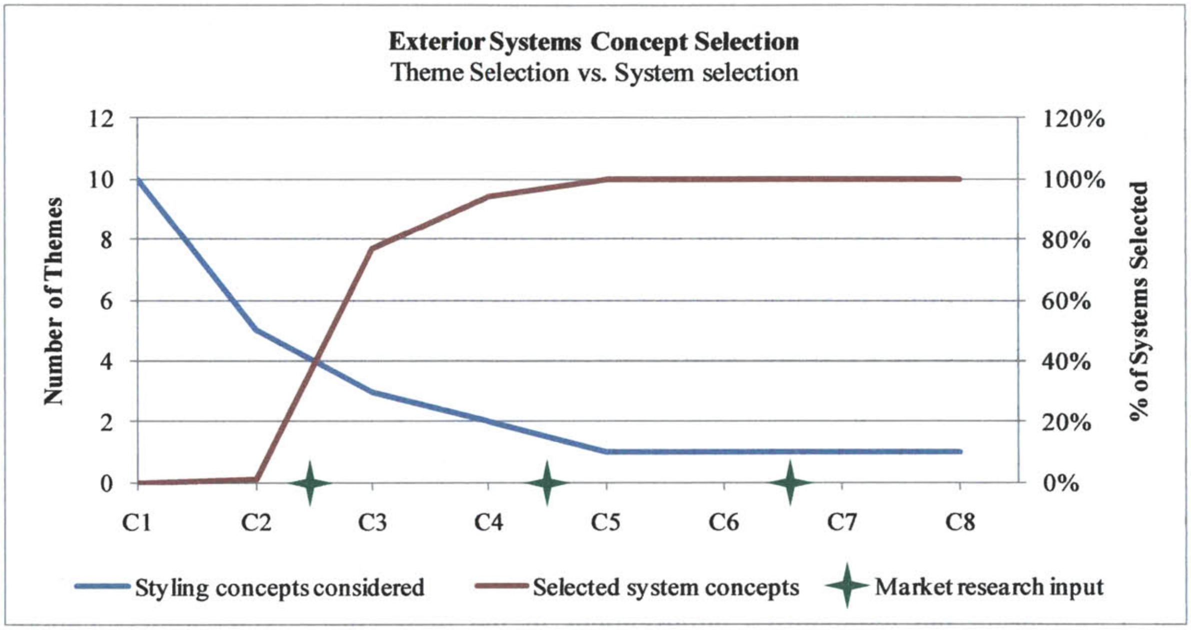


Figure 29 - Exterior Systems concept selection progression (Styling vs. Function)

At C3 77% of the Exterior systems are selected while there are still three *Themes* considered. Once a concept is selected the team iterates over it to implement the *Theme*. An early functional concept selection helps to reduce uncertainty and to set "funnel" type boundaries for the *styling* concept. These quick reductions in uncertainty helps the program estimate cost, weight and refine program assumptions. But, constraining the design space too early in the process might lead to sub-optimal solutions once the theme is selected. This risk is accentuated when the styling aspect of the concept is more valuable to the stakeholders than the constraints set up by the concept selection.

In the last few years, AOEM has set up leadership targets for the appearance attribute. To keep track of this goal, Studio stakeholders have set up internal and external mechanisms. The internal mechanisms are benchmarking-based metrics that compare the *Theme(s)* with the best competitors. These metrics are tracked at each gateway. The external mechanism used is market research. In these events, target customers are exposed to the new product and to its competition. Through multiple questions, the team identifies customer preferences. In this process, Studio's objective is to demonstrate that the customers sampled in the market research prefer the new product appearance rather than the competitor's. According to senior management in the Studio organization, the internal mechanism has a proactive purpose while the external mechanism is used as confirmation.

An important fact to consider is that automotive product development projects typically last a few years. During this time, product offering in the market place evolves. Therefore, the competitive set at C1 is not exactly the same at C7. There is risk that a research-winning design at C2 might not be successful at C7. To mitigate this risk, Studio compares the new product with selected products from other segments that hint design trends changes in competitors' portfolios. Despite these efforts, there is an inherent risk in the methodology because value is estimated using comparisons with an evolving competitive set. Considering the competitive environment in the marketplace, stakeholders cannot afford to approve products that do not meet the goals. In this context, the stakeholders have to request *Theme* changes to address the problem.

Early constraints in the design space limit the ability of the team to respond to unexpected changes driven by the appearance of the product or other requirements. In some cases, the appearance change is so drastic that it leads to a sub-optimal or unfeasible solution considering the set of functional concepts selected. In this situation the team has to revisit the concept selection and restart the iterative process to define the system architecture.

Despite significant efforts, AOEM have had several projects that did not meet the appearance leadership goal at the final market research (C6-C7). This caused late *Theme* revisions that led to rework.

3.3.2 Uncertainty is not recognized case by case

Concept Development methodologies should recognize and address uncertainty. Failing to recognize uncertainty when selecting concepts, leads to sub-optimal or infeasible outcomes when unexpected changes occur. The Concept Development process used by AOEM does recognize uncertainty in system requirements along concept progression. As an example, Figure 30 shows the variation allowed in the geometric requirements of Exterior Systems along the project. The horizontal axis shows gateways C1 to C8 and the vertical axis displays the variation range allowed in the geometric requirements. Data is normalized using a 0-5 scale to avoid disclosing details about the proprietary methodology. A variation range of +/- 0 implies a fixed requirement, no uncertainty. In contrast, a variation range of 5 is assigned to the maximum allowed variation range. The line in "green" shows the allowed variation range in the A-surface and the line in "purple" shows the allowed variation of system and attribute requirements. These variation limits are used in all programs at AOEM.

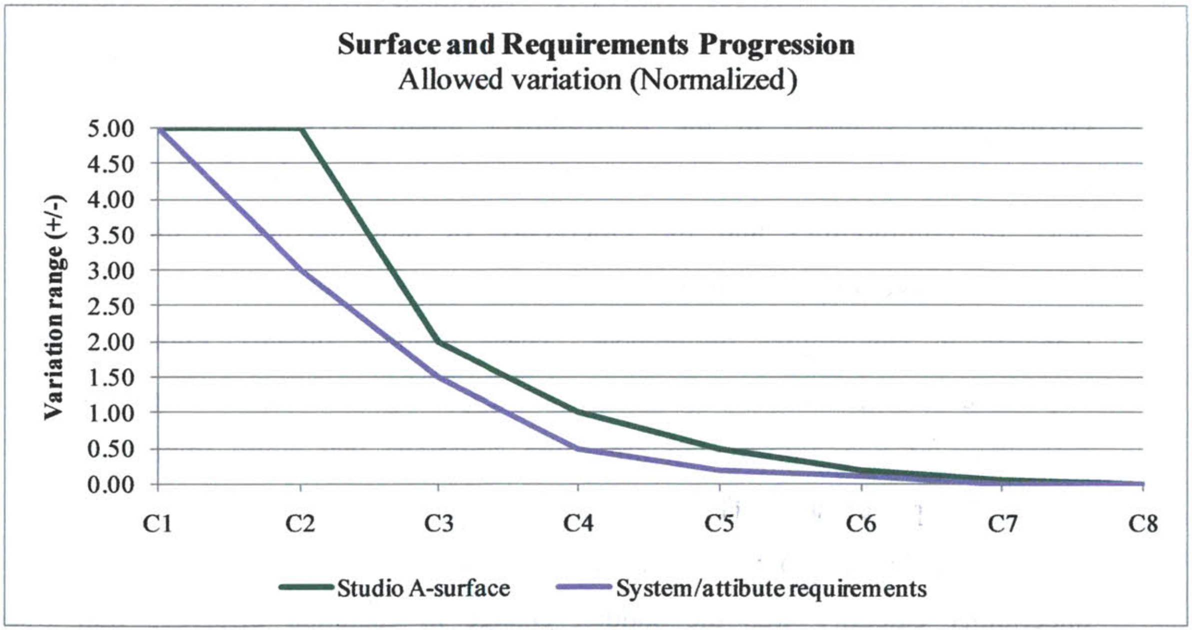


Figure 30 - Allowed variation in Requirements and A-Surface

The positive aspect of this methodology is that the PD team knows what to expect according to the gateway, which is helpful when handling multiple projects with different time lines. But, this method forces the uncertainty in geometric requirements to fit within the allowed limits and does not recognize the "real" uncertainty that remains in the systems, which is different from program to program

In this research, the author identified the following uncertainties that affect system requirements:

- Changes in standards and regulations. Although standards and regulations do not change without notice, there are situations where these are sources of uncertainty. When a new standard or regulation is under development, it might add variability to system requirements. For example during the development of SAE J1772 which standardizes geometric parameters of charging ports in the US market (Society of Automotive Engineers , 2010), AOEM had to recognize and address uncertainty in requirements such as port size.
- Changes in business environment. The automotive business environment is formed by multiple industries that affect or are affected by automotive products. Raw material producers, insurance companies, component suppliers, energy companies and even consumer electronics manufacturers are part of the automotive business environment. Changes in the environment might drive changes in system requirements. The emergence of new technologies/products, drastic changes in the price of commodities and the emergence of new players in the business environment are some examples of business environment changes.
- Changes in stakeholder preferences. These changes directly impact system requirements. Revisions to corporate strategy, organizational changes or the emergence of new information are some situations that could impact internal stakeholder preferences. This uncertainty category also includes the shifts in external stakeholders' preferences, such as the target customer. An example of this uncertainty category was the sudden change in customer priorities that was experienced during the 2009 crisis in the auto-industry. A general economic downturn in the US market combined with peaks in gas prices made fuel economy one of the top priorities of customers. As a consequence AOEM adjusted system requirements such as system weight to enhance the fuel economy attribute.

- Competitor's new product offering. The renovation and addition of new competitors affect those system requirements that derive from qualitative goals. As explained in this chapter, qualitative goals are set by benchmarking. The renovation of a product in the competitive set might "raise the bar" and require a more aggressive system target.

The uncertainty categories discussed above are clearly product specific. Each product deals with a different competitive set, different technologies and stakeholders. Fixed boundaries for variation in system targets do not capture all uncertainty cases. Uncertainties that are not recognized cannot be addressed.

3.3.3 System to system interaction is not considered in concept selection

The formal tools used by AOEM to select functional concepts are configured to evaluate isolated concept sets. Typically, functional concept selection tools are used to select concepts at the third or fourth level in the system decomposition. These tools estimate the effect of the concept at the attribute level. But, system to system interactions are not formally considered in these tools. During AOEM's process review the author identified an integration gap between the system and vehicle-level tools. For example, functional concept sets for fascia, hood, headlamp and fender systems are evaluated in four different decision matrices. These decision matrices evaluate concept performance relative to cost, weight, quality and several vehicle attribute goals. But, the tools available do not allow evaluating the concepts when these systems interact as a front end. The set of concept selection tools used by AOEM might overlook the best concept globally by focusing on selecting the best but isolated lower order concept alternatives.

3.4 Classification of problems in the conceptual design process

The analysis conducted in 3.3 and the information gathered during the literature review, helped identify problems that constrain value delivery and generate waste in the Concept Development process. Four classes of problems were identified; one is associated with the generation of concept alternatives and the rest with concept selection. Table 4 shows this classification.

Concept Development step	**Problem class**	**Description**
Generate concept alternatives	**I**	Design space is not comprehensively explored
Concept selection	**II**	Lack of thoroughness in concept selection
	III	Uncertainty is not considered in concept selection
	IV	The alternative set is oversized

Table 4 - Concept Development problem classification

Class I – Design space is not comprehensively explored

Maximization of value delivery in the Concept Development process requires configuration of the best possible concept. To accomplish this, the design space should be comprehensively explored in the concept generation step. In this thesis, the term *design space* is used to name ALL the possible solutions to a design problem that are feasible within the known constraints. Class I problems enclose two scenarios. In the first, the design team considers only a small subset of the potential alternatives in the available design space. In the second, the concepts generated have the same design parameters. The term *design parameter* is used to name the controllable variables that affect the functions of the concept. In both cases, the consequence is to overlook the best concept because there is less of a chance of finding it. The second scenario has the additional consequence of resource waste. Two concepts with the same design parameters are likely to converge into the same solution, yielding the same outcome as if only one of these concepts were progressed.

Class II – Lack of thoroughness in concept selection

This problem class was first identified by Pugh (1981) as a manifestation of conceptual vulnerability. Class II problems are associated with the concept selection step and involve the following scenarios:

- The concept selection process does not consider all aspects of value delivery
- The concept selection is not well founded

In the first scenario, the evaluations used to select the concept omit relevant goals/requirements. The second scenario considers a concept that was selected without a thoughtful process and/or the decision is not well supported by the concept evaluations. Both scenarios yield sub-optimal or infeasible solutions. This problem cannot be fixed in downstream processes.

Class III – Uncertainty is not considered in concept selection

Not considering uncertainty during concept selection can diminish the value delivered by a concept and generate waste in the development process. Typically during concept selection, the design team compares the performance of each concept relative to selection criteria in order to find the best concept, the one that yields the highest value. But the occurrence of "unexpected" events or the discovery of new information later in the process might alter the perception of value. A concept that was once the best might become sub-optimal or infeasible once uncertainty unfolds.

Uncertainties affect the perception of value either by changing the value definition or by modifying value appraisal. Table 5 maps the identified uncertainties to these two categories. Uncertainties that affect the definition of value were discussed in 3.3 and imply unexpected changes in what the stakeholders consider valuable. Therefore, these uncertainties drive shifts in system goals/requirements.

Uncertainty in the Concept Development process	*Uncertainty in the definition of value*	• Changes in standards and regulations • Changes in business environment • Changes in stakeholder preferences • Competitor's new product offering
	Uncertainty in the appraisal of value	• Error in the instrument to assess value • Undefined system environment

Table 5 - Uncertainty in the Concept Development process

Uncertainties that affect the appraisal of value include:

<u>Error in the instrument to assess value</u>

Value in a concept is estimated by measuring its performance relative to system goals and requirements. If the combination of concept data and measurement instrument has poor accuracy, the assessment of value might be significantly different at the concept phase than at the time the design achieves its full development.

Undefined system environment

During Concept Development the design of the new systems is not defined. This affects the assessments of those aspects of value that are sensitive to the environment of the system. In the conceptual phase, the team often makes assumptions to help complete value assessments. Therefore, the estimate of value can be significantly different at the concept phase than when the environment of the system is fully defined.

In the Concept Development process there are three strategies to manage uncertainty: delay concept selection, implement robustness or embed flexibility in the selected concept. If uncertainty is not recognized and addressed during the Concept Development process, the team might discover during the detail design phase that the selected concept is sub-optimal or not feasible, leading to rework.

Class IV – The alternative set is oversized

The Concept Development process requires time and resources. During the *Concept Selection* step, the team progresses the concepts and conducts the value assessments. The more concepts that are considered during concept progression/evaluation the more time and resources are required. If the amount of concepts that remain in the process exceeds the capabilities of the team or the time allocated to the concept phase, the completeness and quality of the data to support decision making might be adversely affected. Consequently, the team could make the wrong choice.

The Concept Development methodology presented in this thesis addresses problems class I-III and provides recommendations to prevent class IV problems.

Chapter 4 - Value Definition and Concept Generation

4.1 Methodology overview

This thesis proposes a methodology to undertake the conceptual design of automotive Exterior Systems considering two general goals: maximization of the value delivered to the stakeholders and reduction of waste in subsequent activities in the PD process. In order to achieve these goals, the concept development processes of AOEM were analyzed to identify the problems that constrain value delivery and generate waste. In this analysis, general and AOEM-specific concept development problems were identified. To address these problems, the methodology presented in Figure 31 was configured. As reference, this layout maps the four major steps in the conceptual design process presented in 1.1: *Value Definition*, *Concept Generation*, *Concept Selection* and *System Architecture Definition*.

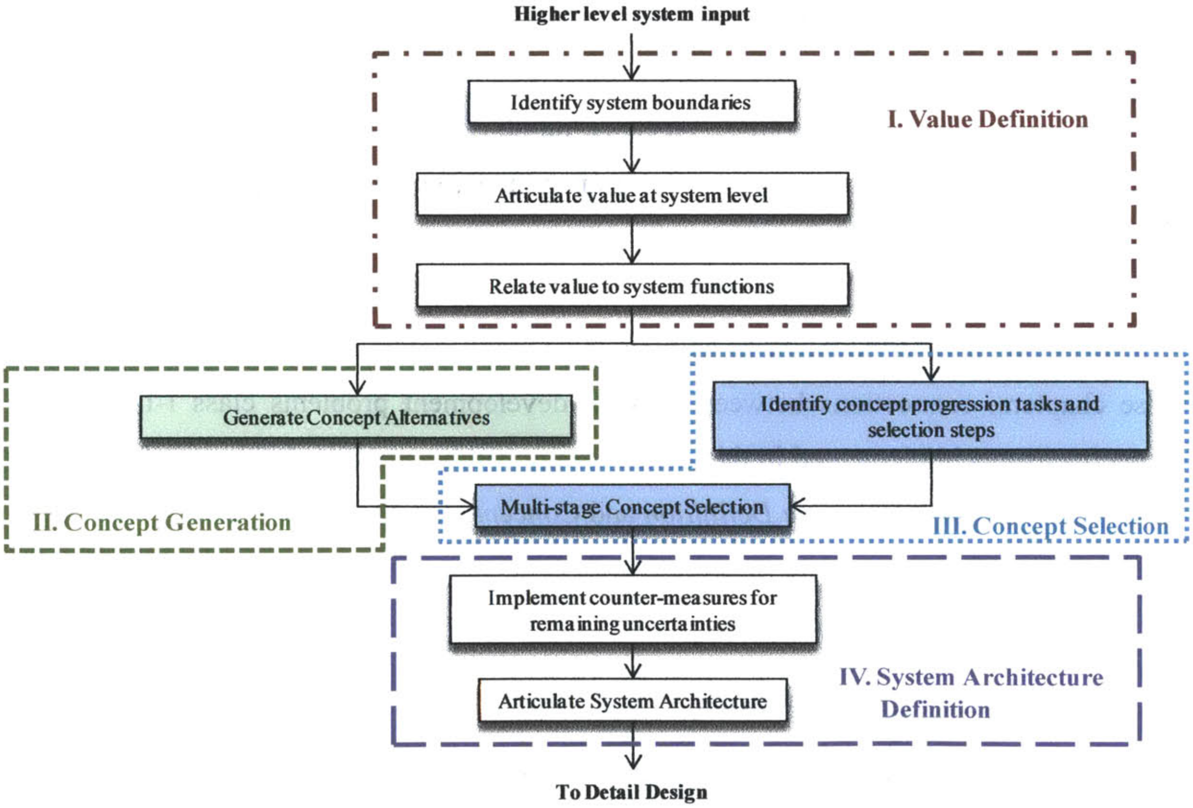


Figure 31 - Layout of proposed methodology

The specific intent of this methodology is to prevent the occurrence of concept development problems class I, II and III, which are described in Chapter 3 (Table 4) and to address the AOEM-specific problems defined in 3.3. Addressing class IV problems in a formal way is outside the scope of this thesis. However, recommendations are provided to handle class IV problems.

The proposed methodology was configured to address the concept development sub-process *System Feasibility*, described in Chapter 3 (3.2.2). Recognizing the fact that *System Feasibility* is coupled with the sub-processes that develop the *styling* aspect of the concept, the proposed methodology requires constant information exchange between the groups executing each sub-process. In addition, inputs from *Theme Development* and *Theme Execution* and *Study Compatibility* will be treated as system requirements, assumptions and constraints.

As explained in Chapter 3, AOEM uses the principles of the System Engineering V model (Figure 27) to decompose the vehicle and manage its complexity during the PD process. Therefore, the proposed process has been configured to work in multiple levels of system decomposition. This methodology receives inputs from higher-level systems (goals, assumptions and constraints) and provides an output (the system architecture) to lower order systems and downstream processes.

Chapters 4 and 5 describe the tasks and tools that constitute this methodology. Throughout these chapters, connections between concept development problems class I-III and the countermeasures implemented in this methodology will be articulated. Chapter 4 addresses the first two major steps: *Value Definition* and *Concept Generation*.

4.2 Value Definition

4.2.1 Identify system boundaries

The first task to define value is to identify the boundaries of the system that is being conceptualized. In this effort, system developers should determine the type of project that will be carried out. This can be done using the assumptions and constraints obtained as inputs and the project categories described in 3.1.2. This approach is critical to assure an understanding of the nature and the amount of systems that have to be developed as part of the project. The development team must consider this information and the human resources available in the determination of the system decomposition required to properly manage the conceptualization of the system. The system boundaries for the Concept Development process are defined by this decomposition.

To illustrate how system decomposition is related to the project category, the partition method used by the Studio Engineering group at AOEM is considered. As information, Studio Engineering is a system integration activity that focuses its efforts on management of the interaction between the *styling* and the *functional* aspects of the concept throughout the development of Exterior Systems. To manage the information involved in a *Body & Platform Development* project (all-new exterior and platform) Studio Engineering partitions the vehicle into three lower order systems: vehicle front, roof/sides and vehicle rear. The same partitions are applied to a *Platform Derivative* project (all-new exterior, minor platform changes). In contrast, the information required for concept development in a much smaller project such as a *Product Derivative* (special edition in a nameplate) can be managed without decomposing the entire system. *Mid-cycle update* projects typically partition the product into two lower order systems: front and rear. New systems surrounded by platform components or legacy systems can be treated in isolation during concept development.

An important benefit of this method is that it groups Exterior Systems in such a way that both the physical interfaces (e.g. attachment, location or energy transfer) and the attributes that emerge from the interaction of these systems can be analyzed. For example, a front-end system clusters lower order systems such as the front fascia, fenders, headlights and hood. This cluster enables the study of the physical interfaces among systems (margins, attachments, locators) and the *craftsmanship* attribute that emerge from these interfaces. In another example, the front-end system allows the analysis of the structural performance in the front fascia as well as the *pedestrian protection* attribute that result from the interaction of shape and structural characteristics of fascia, headlights and hood.

The methodology proposed in this thesis adopts the system decomposition method used by Studio Engineering because of its compatibility with AOEM's organizational structure and methods. Also, this system decomposition contributes to address one of the AOEM-specific concept development problems identified in Chapter 3 (3.3.3). This system decomposition method addresses the concept integration gap identified between the functional conceptualization of third and fourth order systems and vehicle styling concepts.

For special projects that cannot be categorized using the project classification discussed in 3.1.2, it is recommended that a component DSM matrix (described in 2.1.1) be used to model interactions among systems. The analysis of this model will help determine the system decomposition that should be used during concept development. A *clustering* technique is suggested to accomplish this goal.

4.2.2 Articulate value at system-level

Once the boundaries of the system to be conceptualized are understood, value is articulated at system-level. To achieve this, the system integrator must identify the requirements that the system should address. At system-level, the set of requirements is integrated considering the following inputs: program assumptions, goals from higher level systems (vehicle attribute requirements) and system-specific requirements. Program assumptions are information elements that define the features in the new product, the markets where the product will be sold and project constraints (e.g. use of legacy and platform systems). System-specific requirements are generated by stakeholders that belong to the system engineering groups. The purpose of these requirements is to assure proper system function and failure mode prevention.

At AOEM, there are multiple documents that provide the inputs required to integrate the set of system requirements. Attribute-related requirements can be extracted from the strategies developed by the attribute engineering groups to achieve vehicle goals. System-specific requirements are articulated in multiple checklists. Using this information, the team developing the concept should state the requirements from the perspective of the system being conceptualized. This should be done in solution-neutral terms, when possible. A few examples of requirement statements for a front-end system are:

- "The front end system must be compliant with NHTSA part 581".
- "The lighting elements in the front end must be compliant with FMVSS 108".
- "The minimum front down vision angle that the front end should allow is XX deg".
- "The minimum clearance between the front bumper beam and front end components is YY mm".
- "The minimum opening area in front of heat exchangers is XXX cm^2".

As explained in 3.2.1, goals and requirements are subject to change along the Concept Development process. These changes are driven by concept progression and the elements of uncertainty in the system. Therefore, the system development team must constantly monitor the system requirement inputs.

System modeling

The methodology proposed in this thesis requires a modeling tool that maps the relationships among system requirements, system functions, objects (subsystems) and concept progression activities. To address this need, a subset of the DSM and DMM matrices that form Bartolomei's ESM (Bartolomei J. , 2007) is used. Although the author finds the ESM a comprehensive tool to model system interactions, a few changes have been made to fit the proposed concept development application. Specifically, these changes are related to the interpretation of the interactions modeled in the matrices. In addition, a sequence to create and analyze these matrices is proposed considering a concept development application. Figure 32 depicts the subset of matrices and the sequence used for system modeling in the proposed methodology.

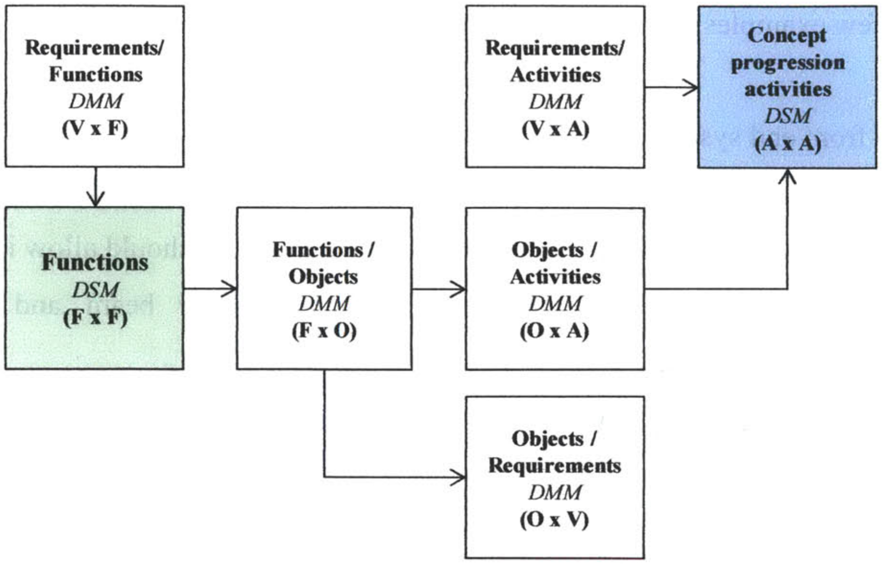


Figure 32 – Matrix-based system modeling tool used in proposed methodology

4.2.3 Relate value to system functions

In this task, the system development team identifies the functions the system must perform to meet the articulated system requirements. This methodology uses the Requirements x Functions DMM matrix (**V x F** in Bartolomei's framework) as an instrument to complete this thought process. To construct this matrix, column headers are populated with the system-level requirements. After analysis of these requirements, the system development team completes row headers with the functions the system must perform in an effort to address the requirements in the columns. Matrix construction is completed by filling-in the row/column intersections with "1s" where an interaction exists. To clarify the interpretation of these interactions with an example, assume there is an interaction between the requirement in column *x* and the function in row *y*. This interaction should be read: "To meet the system requirement in column *x*, the system must perform the function in row *y*".

4.3 Concept Generation

The next major step in the conceptual design process is the generation of multiple concepts for the system. *Generate Concept Alternatives* is the task that corresponds to this step in the proposed methodology. This task uses the functions identified in 4.2.3 as inputs and provides a set of concept alternatives as an output. *Generate Concept Alternatives* involves three second order tasks: *Define system concept layers*, *Configure concepts* and *Define concept sets*. The layout in Figure 33 shows the relationships between these second order tasks and the inputs required for its execution. Furthermore, the task *Generate Concept Alternatives* is configured to prevent the occurrence of Class I conceptual design problem, "Design space is not comprehensively explored". As explained in 3.4, this conceptual problem class encloses two scenarios. In the first, the design team considers only a small subset of the potential alternatives in the available design space. In the second, the concepts generated have the same design variables.

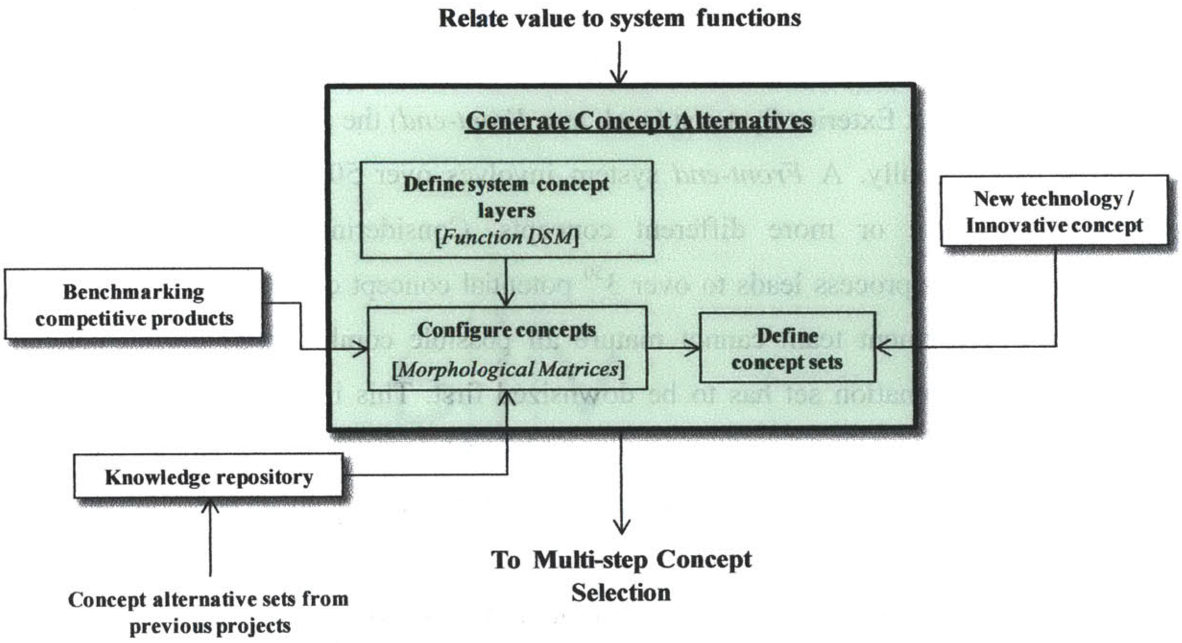


Figure 33 - Task decomposition: Generate Concept Alternatives

4.3.1 Define system concept layers

Concept generation and concept selection involve creative, data processing and decision making processes that are mostly executed by humans. Because of the cognitive limits of the executors, managing the conceptualization of complex systems that consider a large number of requirements and functions is very challenging to undertake. In the field of Psychology, Miller (1956) acknowledges that the amount of information that humans can process correctly is limited by the "span of absolute judgment" and the "span of immediate memory". The first term, "span of absolute judgment" refers to the maximum amount of different magnitudes a human can identify accurately when subject to a variable stimulus.

The second term refers to the maximum amount of "chunks" of data that humans can retain after being exposed to information. Several experiments showed that the span for both constraints is about seven.

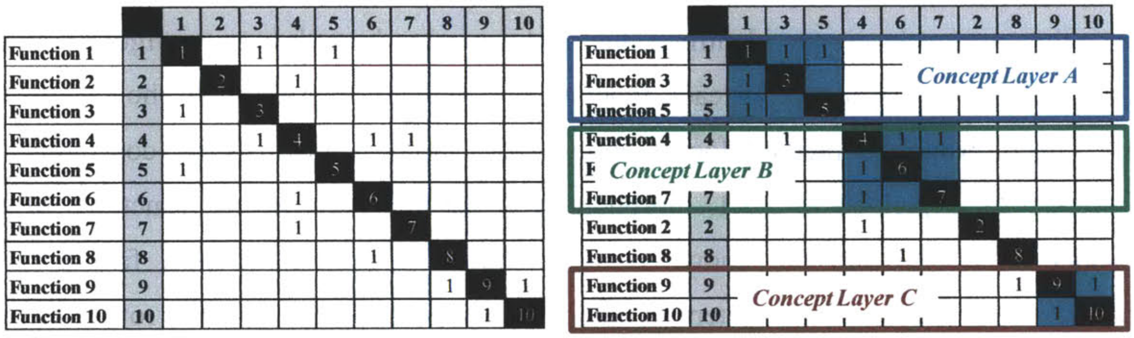
To show the effect of system complexity in the amount of information that has to be processed during conceptual design, consider the second order task *Configure concepts*. In this task, morphological matrices (discussed in 2.2.1) are used to generate system concept alternatives. These matrices organize the known means (concepts) to perform each system function. A concept alternative for the system is configured by selecting a combination of means that perform all system functions. But, when this tool is applied to configure concepts for complex Exterior Systems (such as a *Front-end*) the amount of data generated can grow exponentially. A *Front-end* system involves over 50 functions; each can be performed by three or more different concepts. Considering all system functions simultaneously, this process leads to over 3^{50} potential concept combinations. Obviously, the system development team cannot mature all possible combinations during concept selection; the combination set has to be downsized first. This involves data analyses in which developers recognize dependency relationships among concepts, discard incompatible combinations and select the best alternatives. Considering human data processing limitations, system developers and stakeholders would not be able to do make effective judgments if exposed to excessive amount of data at the same time.

To handle this situation, this methodology uses a DSM matrix configured with the functions identified in the Requirements x Functions DMM. This Function DSM is used to find *concept layers* that assist managing the function complexity of the system during concept development. The term *concept layer* is used to name a group of functions that should be considered together in the concept development process because of the interactions that exist among the known concepts to perform these functions. An interaction between functions is mapped in the DSM if one of the following statements is true:

1) There is a need to know which concept is considered to perform one of the functions in order to conceptualize another.

2) Both functions have been integrated into the same object before. In this case, the functions should be considered interdependent.

Once the DSM has been populated with all system functions and interactions, a sequencing algorithm (discussed in 2.1.1) is used to reorder the functions in order to concentrate interactions closer to the diagonal and reduce the interactions located to the right of it. As a result, feed-forward flow in the sequence is maximized and clusters of interdependent functions are found. Figure 34 depicts an example of a Function DSM used to determine *concept layers*. The left side shows the DSM before the sequencing algorithm is applied and the right shows the DSM after partition.



		1	2	3	4	5	6	7	8	9	10
Function 1	1	1		1		1					
Function 2	2		2		1						
Function 3	3	1		3							
Function 4	4			1	4		1	1			
Function 5	5	1				5					
Function 6	6				1		6				
Function 7	7				1			7			
Function 8	8						1		8		
Function 9	9								1	9	1
Function 10	10									1	10

		1	3	5	4	6	7	2	8	9	10
Function 1	1	1	1	1							
Function 3	3	1	3								
Function 5	5	1		5							
Function 4	4		1		4	1	1				
F					1	6					
Function 7	7				1		7				
Function 2	2				1			2			
Function 8	8					1			8		
Function 9	9								1	9	1
Function 10	10									1	10

Figure 34 - Identifying concept layers using the Function DSM

To further clarify how interactions are mapped in the Function DSM, two examples are used. In the first example, the interaction mapped in the intersection of column 4 and row 2 is considered. Here, the system development team requires knowledge of how Function 4 was conceptualized in order to configure the concepts for Function 2. In the second example, it is assumed that Functions 9 and 10 have been integrated into the same object before. In this situation, the functions are mapped as interdependent.

The right side of Figure 34 shows the DSM after the sequencing algorithm is applied. The partitioned DSM uncovers three concept layers (labeled A, B and C) and a sequence to guide concept generation and concept selection. As result of this analysis the system development team learns that Functions 1, 3 and 5 (layer A) should be considered together when configuring concepts. Also, that Layer B should be conceptualized after Layer A because Function 4 requires input from Function 3. Functions 2 and 8 are not involved in any *concept layer* but are involved in a sequence.

The application of the Function DSM allows system developers to handle the information related to the conceptualization of a complex system by decomposing it into simpler elements, while still considering interactions within the system. Instead of considering all system functions simultaneously in a single analysis, developers conduct a series of similar analyses in which humans are exposed to manageable amounts of information.

4.3.2 Configure concepts

Once the *concept layers* are identified, the next second order task is to configure multiple concepts for each layer and for each function that remains ungrouped. In the case of the layers, the proposed methodology applies morphological matrices to configure the concepts. As explained in 2.2.1, morphological matrices organize the functions of the product or system and the known design solutions that perform each function. To configure a concept for the system, a design solution is selected in each row. Multiple concepts can be generated by using different design solution combinations. To construct the morphological matrix, the row headers are populated with the functions to be conceptualized. Each cell on the right in the same row shows a different design solution (concept) that performs the function in the header. Figure 35 shows an example of a morphological matrix constructed for *Concept Layer "A"* identified in the Function DSM in Figure 34.

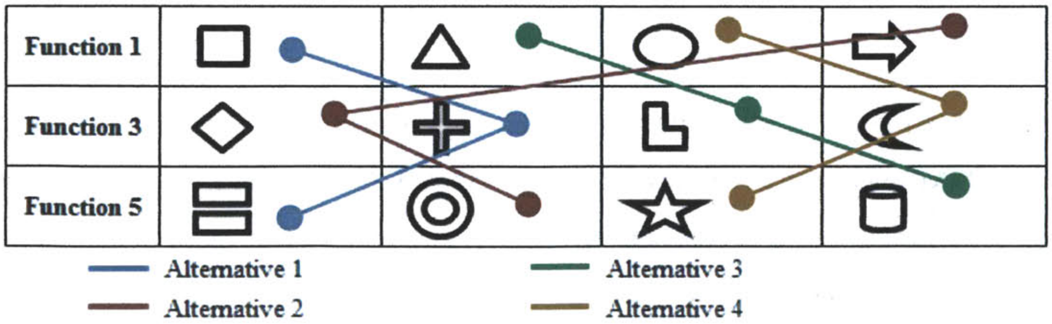


Figure 35 - Morphological matrix for concept layer A

The three functions identified in *Concept Layer "A"* are populated in the row headers. The cells in the first row show a graphic representation of each known design solution to perform Function 1. A concept for layer "A" is configured by selecting one design solution from each row. Figure 35 shows four concept alternatives configured for layer "A". The information to build each row is gathered through the two channels described below:

1) Corporate knowledge (Design repositories). Over the years, AOEM has accumulated a plethora of information about its products. Reliability, testing and CAD data is available for the systems developed for its current and past products. In addition, AOEM has a constant flow of product development projects, multiple projects are carried out simultaneously. Current and past projects provide a large database to support the creation of morphological matrices.
2) Benchmarking. In addition to enable attribute target setting, benchmarking is also a source of ideas for concept generation. It is typical in the automotive industry for corporations to dedicate resources to gather information about competitive products. In fact, companies like A2Mac1[12] are dedicated to the generation and management of automotive benchmarking data. AOEM engineers have at their disposal an extensive database of benchmarking data including pictures, tear down analyses and CAD data that can be used to identify design solutions for the development of morphological matrices.

The morphological approach was selected as the concept generation tool for the following reasons:

- Morphological matrices fit the analytic process used by the product development engineers at AOEM to conceptualize systems. When facing a concept development problem, engineers at AOEM look for known/proven solutions that could be compatible with the new environment through modification of the concept control parameters. As explained by one of the engineers interviewed, this approach allows configuration of concepts that can be matured in an environment with challenging

---

[12] A2Mac1 Automotive Benchmarking www.a2mac1.com

timing, cost and quality demands from the stakeholders. Morphological matrices enhance this approach by decomposing the known solutions into concepts, organizing these concepts per functions and generating new system configurations by recombining the known concepts.

- Morphological matrices can also be adopted to store knowledge that can be utilized in multiple projects. In a mature industry in which dominant architectures have emerged (e.g. body styles and vehicle categories), the performance envelope of most Exterior systems have evolved through incremental innovations. In most cases, these innovations are first implemented in the highest level products and are gradually deployed to the base ones. Therefore, a set of concepts identified to address a given function can be used to configure various system concepts in multiple projects. In addition, morphological matrices have shown potential for becoming a platform for design repositories and automated concept generation tools. These can help accelerate the concept generation process and facilitate knowledge transfer throughout the organization.

4.3.3 Define concept sets

The objective of this second order task is to define a set of concepts that will be matured and iteratively evaluated during the *Concept Selection* process. To achieve this goal, the first step is to downsize the concept set created using the morphological matrices developed in the previous task. Through the combination of design solutions, a morphological matrix can configure a large number of concepts for the system. For example, the morphological matrix shown in Figure 35 has the potential to create 81 different concepts (assuming there are no dependencies or conflicts among the concepts). This is still a large number of alternatives that cannot be handled during the concept selection. Therefore there is a need to reduce the number of concept alternatives considered in the process.

Pare down concepts sets

The proposed methodology for concept development considers the following criteria to pare down the concept set:

Discard concepts not compatible with the concept development inputs

While generating combinations of design solutions using the morphological matrices, the system development team should discard the combinations that are clearly not compatible with the inputs received from other processes. As explained earlier in this chapter, the proposed methodology is focused in the *System Feasibility* sub-process that is conducted to conceptualize the functional aspect of Exterior Systems. This sub-process receives inputs from *Theme Development*, *Theme Execution* and *Study Compatibility*. As discussed in Chapter 3, the input provided by the first two sub-processes is related to requirements of the *styling* aspect of the concept. These requirements are articulated in the form of imagery and CAD data. Depending on the point in time when this input is provided, it can be related to one or more *styling* concepts. The system developers should discard the combinations that are clearly not compatible with the set of *styling* concepts. Another input that should be considered in this analysis is provided by the *Study Compatibility* sub-process, which develops the functional aspect of the concept at vehicle-level. The input received from this process includes a set of project assumptions and constraints. Target markets, product features, legacy and platform systems are some of these assumptions. When generating concepts with the morphological matrices, any combination that is clearly not compatible with these assumptions should be discarded.

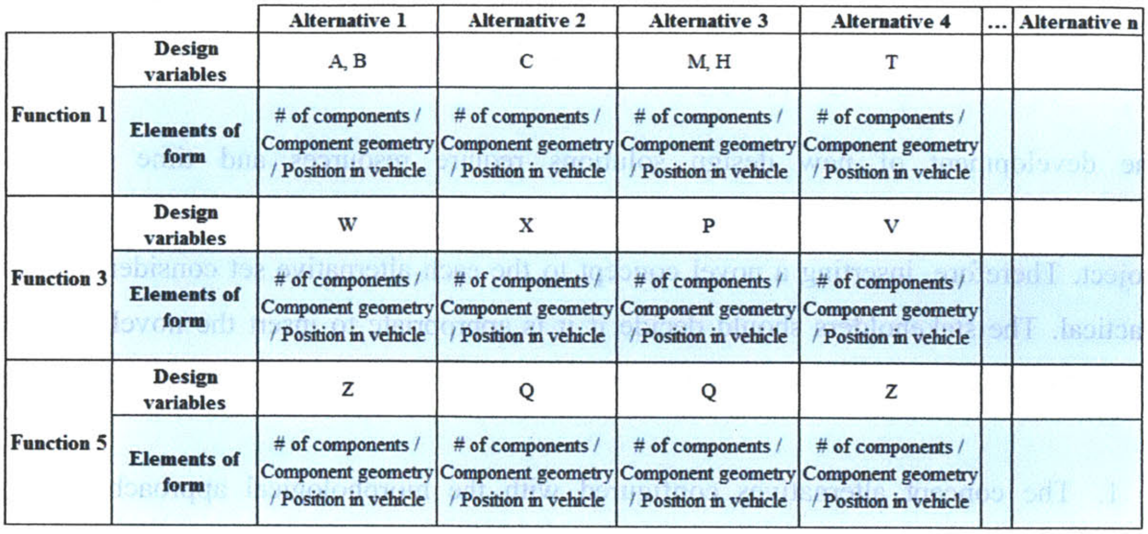
Maximize concept differentiation

The next criterion for downsizing the alternative set is to pre-select the concepts that best fit the process inputs while maximizing the differences among the concepts. The objective of this procedure is to enhance efficiency in the concept development process: keep the design space as large as possible while reducing the number of alternatives considered. The proposed methodology looks for concept differentiation in its design variables and elements of form.

The design variables of a concept are the ones that the system developers control in order to perform the related system functions. The elements of form include the number of components, the geometry and the position in the vehicle. In the context of Exterior Systems, the concept's design variables and elements of form define its design space. The design space of a concept refers to ALL the feasible value combinations that design variables can take given the concept's elements of form and the known constraints. The design space of a concept defines its potential for value delivery, which is not accurately known at this point in the process. The design space of the concept alternatives aggregate to form the design space of the concept set.

It is expected that a pair of concepts that have similar parameters and elements of form will have, to some extent, overlapping design spaces. By selecting concept alternatives with different parameters and elements of form, the system development team will reduce the chances of having overlapping design spaces among the concept alternatives in the set. As a consequence, downstream processes will consider a larger design space while keeping a manageable number of concept alternatives. Considering a larger design space translates to more opportunities to find the feasible system concept that yields the highest value to the stakeholders.

Figure 36 shows a table that could be helpful in the comparison of design variables and form elements of the concept alternatives in the set. To construct this table, the first step is to populate the row headers with the functions considered in the morphological matrix. Next, the columns to the right should be filled with the design variables and the form elements of the concept alternatives that remain the set (after the first concept pare down criterion was applied). Each column should be related to one concept alternative. Once built, this comparison matrix helps to visualize similarities between design variables and elements of form in order to assist the selection of those few concepts that best fit the inputs of the process and maximize concept differentiation



		Alternative 1	Alternative 2	Alternative 3	Alternative 4	...	Alternative n
Function 1	Design variables	A, B	C	M, H	T		
	Elements of form	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle		
Function 3	Design variables	W	X	P	V		
	Elements of form	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle		
Function 5	Design variables	Z	Q	Q	Z		
	Elements of form	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle	# of components / Component geometry / Position in vehicle		

Figure 36 – Concept comparison table, design variables and elements of form

Inserting a novel solution to the concept set

Morphological matrices enable the system development team to capitalize on a large knowledge base of design solutions in the generation of concept alternatives for the new system. In addition, this tool allows configuration of multiple system concepts in a short time and with some confidence concerning their feasibility. Along with these benefits, this tool has a disadvantage relative to the generation of innovations. Morphological matrices have potential to yield novel system concepts through new combinations of design solutions. But, the configuration of new ways to perform functions is out of the scope of the morphological approach. The author recognizes that the thought process involved in the morphological approach could trigger creativity and produce a new design solution. However, these situations are unpredictable.

In a competitive marketplace, innovations are important to differentiate the product. Moreover, innovations are critical to expand the catalogue of design solutions available to a product development team. This mechanism is required to remain competitive. Recognizing these facts, the proposed methodology considers the insertion of a novel concept to the concept alternative set. This should be done after the alternative set has been pared down and whenever the stakeholders consider it adequate. A process external to the system development team is assumed to conduct the ideation of this novel concept.

The development of new design solutions require resources and time to reach implementation readiness. Typically, these elements are scarce in a product development project. Therefore, inserting a novel concept to the each alternative set considered is not practical. The stakeholders should decide if it is appropriate to insert the novel concept. The author suggests the insertion of a novel concept in any of the following scenarios:

1. The concept alternatives configured with the morphological approach are not capable of delivering the value expected by the stakeholders.
2. A new design solution has emerged that has shown potential to significantly improve system performance in one or several aspects of value and its implementation is compatible with the project assumptions (timing, content, etc.).

Scenario 1 can be considered a "technology pull"; the generation of the novel concept is driven by project need. In this situation, a problem solving methodology such as TRIZ (discussed in Chapter 2) can be used to generate the new concept required to address stakeholder needs. On the other hand, Scenario 2 can be considered a "technology push". In this case the technology has already been created and the stakeholders identified an opportunity to complete its development and capitalize it.

In the case of AOEM, three formal channels for innovation are available to its product development teams. The first one is internal to the company: the research work streams established by the advanced research group. AOEM deploys these research resources through a technology development process that delivers new technologies ready to be implemented by a system development team. The second one is the set of research initiatives within the automotive supply base which are external to the company and are also available to AOEM's competitors. The third channel is also external: hiring innovation consulting firms.

4.4 Addressing generic and AOEM-specific conceptual design problems

As stated earlier, the objective of the proposed methodology is to maximize value delivery to the stakeholders and prevent waste in downstream processes. To meet this objective, the proposed methodology implements procedures to prevent the occurrence of problems that constrain value delivery and generate waste. Through the thesis research, the author identified generic and AOEM-specific concept development problems.

The methodology step *Generate Concept Alternatives*, includes several preventive actions to address the Class I concept development problem: "Design space is not comprehensively explored". First, the application of morphological matrices allows the system developers to use a comprehensive knowledge base to generate a large number of concept alternatives for the system. This translates into the exploration of a large design space which increases the possibilities of finding the system concept that delivers the best value to the stakeholders. Second, the pre-selection of concepts using the maximum differentiation criteria, prevents a drastic reduction in the design space when doing the imminent reduction in the number of alternatives. By addressing the Class I concept development problem, a critical constraint for value delivery is removed.

Furthermore, the methodology step *Generate Concept Alternatives* addresses the AOEM-specific problem "System to system interaction is not considered in concept selection" (3.3.3). Through the use of the Function DSM, the methodology identifies dependency relationships among the functions of the system relative to its conceptualization. This enables the system development team to identify a sequence for concept generation and selection. In addition, the use of concept layers allows the developers to manage interdependencies by configuring concepts for clusters of interdependent functions.

Chapter 4 described the first two major steps of the proposed concept development methodology: Value Definition and Concept Generation. The outcome of the Value Definition step is a set of requirements/objectives articulated at system-level. On the other hand, Concept Generation provides a set of concept alternatives to be progressed and evaluated throughout the next major step: Concept Selection.

Chapter 5: Concept Selection and System Architecture Definition

5.1 Concept selection

The next major step in the conceptual design process is selection of the concept that will define the architecture of the system and its sub-systems. This thesis considers a multi-stage concept selection technique in which the set of concept alternatives created in the task *Generate Concept Alternatives* is progressed and gradually reduced until one concept is selected. In each selection step, the stakeholders perform a concept selection analysis to drive alternative set reduction. This analysis involves a decision making process in which the stakeholders consider inputs from quantitative and qualitative evaluations of the alternatives. Between each concept selection step, concept progression activities occur. As a result, uncertainty is reduced as the system development team progresses from one concept selection step to the next.

Figure 37 depicts a layout of the *Concept Selection* process. This process starts with the identification of concept progression tasks and the definition of the plan for the selection steps. Once these have been established, the system development team progresses the concepts defined during *Generate Concept Alternatives* and performs the selection analyses according to plan. The output of this multi-step concept selection process is the selection of a single concept alternative. This is achieved when one concept alternative is selected for every concept layer and non-clustered function.

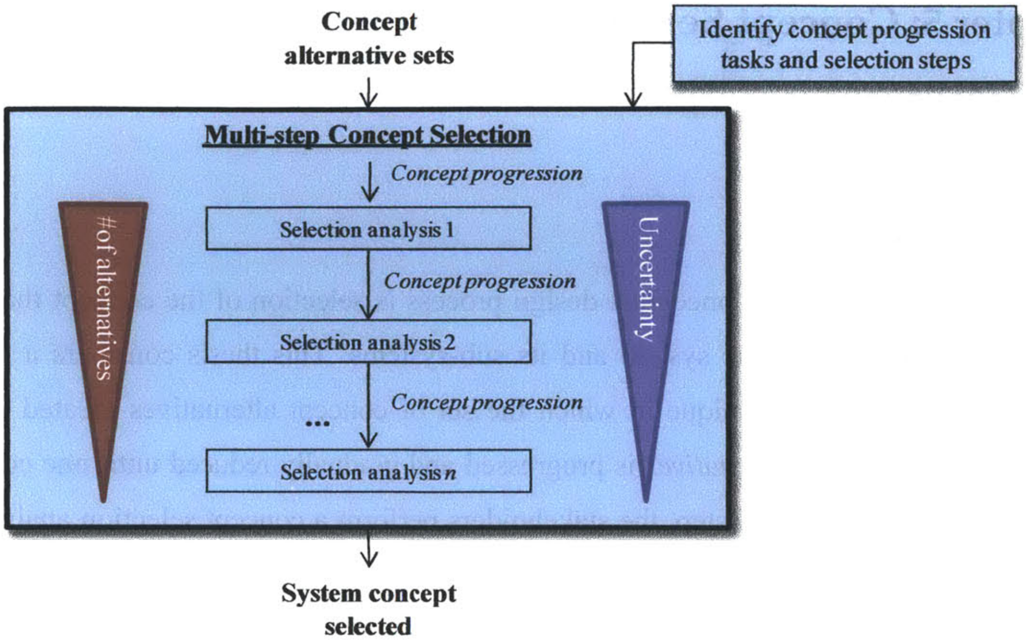


Figure 37 - Multi-step Concept Selection process

5.1.1 Identify concept progression activities and selection steps

This task is initiated once the concept layers have been identified in the Function DSM. Concept progression activities and selection stages are determined using the matrix-based system modeling tool shown in Figure 32 (4.3). Concept progression tasks are activities performed by the system development team to increase design definition and reduce uncertainty. This thesis considers two types of concept progression activities: *Data Progression* and *Evaluation* activities.

Data progression activities

Data progression activities are those that increase the level of definition in the data related to the concept. In the context of Exterior Systems, geometric data (size, shape and position) are critical pieces of information as they define performance relative to most product attributes and aspects of value. Therefore, this methodology considers *Data progression* activities related to the creation of geometric data. As stated in Chapter 3, concepts for Exterior Systems have both *Styling* and *Functional* aspects. Each aspect of the concept has a *Data progression* sequence. Figure 38 summarizes data progression for both aspects of the concept in the context of Exterior Systems.

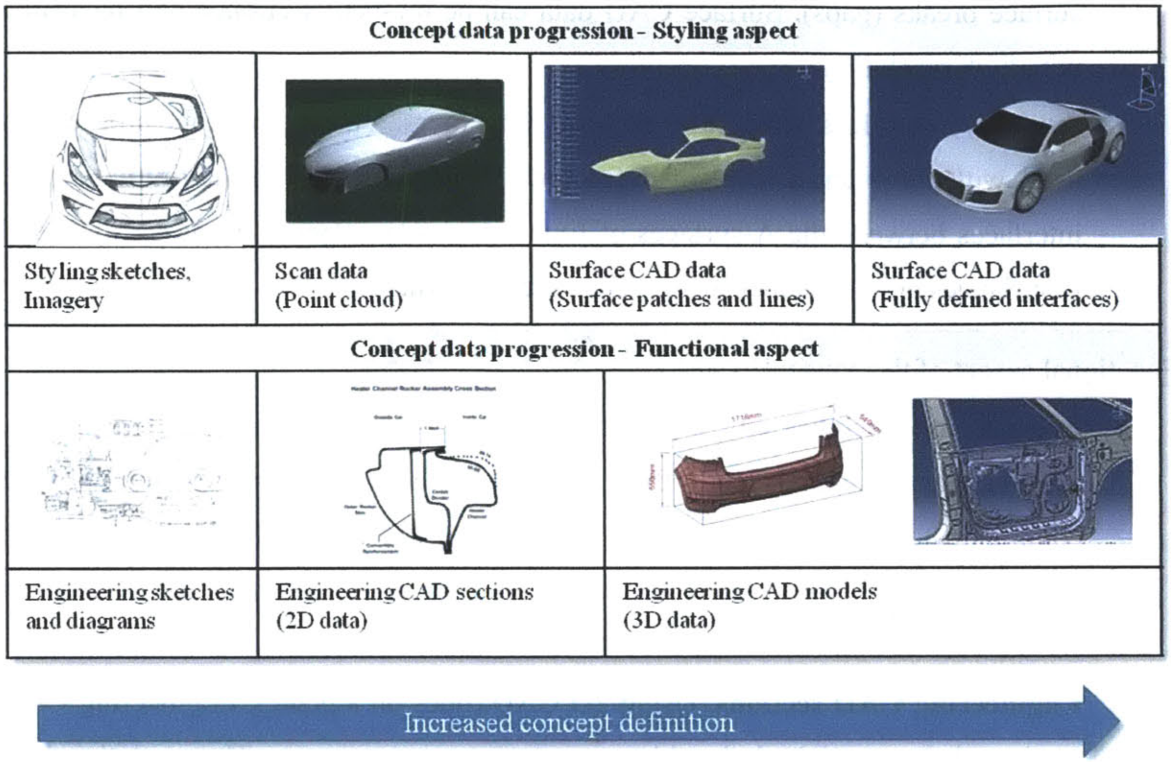


Figure 38 - Data progression tasks: Styling and Functional aspects of the concept

Styling aspect of the concept

- **Studio sketches and imagery.** This is the initial form of data for the *styling* aspect of the concept. Using lines, color and perspective, Studio designers articulate the elements of the *Theme* (styling vehicle-level concept) such as the graphics, proportions and surface treatment. This data cannot be measured, but can be interpreted.
- **Scan data.** Once sketches and drawings have been transformed into physical models, (usually clay models) scans are used to capture the hand modeling work done on the models. Scan data is also known as a "point cloud". This data can be sectioned and measured using CAD tools. Both sections and measurements have rough resolution.
- **Surface CAD data.** The next level in data progression is the Surface CAD data. It is also known as "math data" and represents the A-surfaces of all Exterior Systems in the vehicle. In this level of data, interfaces are defined using lines-on-surface or

surface breaks (gaps). Surface CAD data can be meshed, sectioned and measured with high resolution.

- **Surface CAD data with fully defined interfaces.** This is the data progression level with the highest level of definition. This data shows full definition in the interfaces between the A-surfaces of Exterior systems. Panel flushness, fillets and first flanges are the elements that define these interfaces.

Functional aspect of the concept

- **Engineering Sketches and Diagrams.** This level of data includes all the images, diagrams and hand sketches that are used by the engineering community to communicate the functional aspect of the concept. This level of data allows an understanding of how system functions are performed and how the concept is structured.
- **Engineering CAD sections.** Using 2D CAD (lines on a plane), Engineering CAD sections define spatial relationships among system components. These relationships include attachments, position in-vehicle, clearances and mechanism operation. This CAD data can be measured with high resolution.
- **Engineering CAD models.** This level of data involves the creation of 3D CAD models for both structural and class-A components. This data shows material thickness

Evaluation activities

Evaluation activities are those in which the system development team assesses value in the concepts. This value assessment involves the determination of the performance level of the concepts relative to system requirements. In the context of Exterior Systems, most *Evaluation* activities require geometric data as input. This thesis considers three types of *Evaluation* activities:

- **Theme assessment.** This type of *evaluation* task refers to the feasibility evaluation of the *styling* concepts (*Themes*). Theme assessments involve the evaluation of the *Themes* to the geometric targets and requirements established for the product. *Package* targets are examples of these geometric targets. Theme assessments require CAD data of the *Themes* as input. The lowest level of data progression that can be used to assess the *Themes* is scan data.

- **CAD studies.** In this type of *evaluation* task, CAD tools are used to evaluate the performance of the functional aspect of the concept relative to system requirements. This task category includes both static and dynamic geometric studies (mechanisms). These evaluations need CAD data as input. Depending on the specifics of the study the CAD data required could be sections, surface or solid data.
- **Simulation studies.** This category refers to those activities that involve the use of computer aided tools to simulate conditions to evaluate the performance of the concept and its compliance with system requirements. CAE[13], CAM[14], CFD[15]and other simulation tools are used to accomplish these *evaluation* activities. These studies require three-dimensional CAD data as input (scan, surface or solids, depending on the study). In most cases, this data has to be pre-processed (transformed into a mesh of geometric elements).

Defining concept selection stages

As explained earlier, the first task within the Concept Selection step is to identify the concept progression activities and define the concept selection stages. To achieve this, the matrix-based system modeling tool shown in Figure 32 is used as an instrument. Once the Function DSM has been completed and the *concept layers* have been identified, the next step is to create the Functions x Objects DMM (**F x O** in Bartolomei's framework). This DMM enables the system development team to relate the clustered functions to objects (sub-systems and components). To construct this DMM, the clustered system functions are populated in the column headers. Generic subsystems (objects) populate the row headers. Generic names for the subsystems should be used to avoid references to specific concepts. Interactions are mapped at the intersections of rows and columns by filling-in the cells with "1"s. In this matrix an interaction between column *x* and row *y* should be interpreted as: "The object in row *y* performs or is used to perform the function in column *x*".

---

[13] CAE: Computer Aided Engineering

[14] CAM: Computer Aided Manufacturing

[15] CFD: Computational Fluid Dynamics

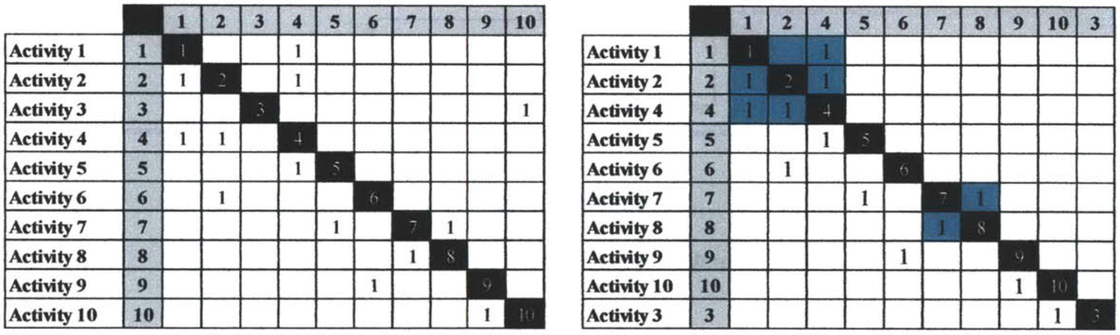
Then, the subsystems identified in the **F x O** DMM are used to create the Objects x Activities DMM (**O x A** in ESM framework). This matrix relates the objects in the system to the related data progression activities. To construct this DMM, system objects are populated in the column headers and data progression activities in the row headers. As in previous DMM models, interactions are mapped by filling-in the row and column intersections with "1"s. In the **O x A** DMM, an interaction between column *x* and row *y* should be interpreted as: "Activity *y* is a data progression activity of object *x*".

Next, the Objects x Requirements DMM should be created (**O x V** in the ESM framework). This matrix relates the objects in the system to system requirements. To build this matrix, the system objects are populated in the column headers and system requirements in the row headers. As in previous matrices, interactions are mapped by filling in row and column intersections with "1"s. In the **O x V** matrix, the interactions between column *x* and row *y* should be interpreted as: "The object *x* affects the system performance relative to requirement *y*". Another interpretation could be: "The object *x* affects system compliance with system requirement *y*".

To complete the identification of concept progression activities, the Requirements x Activities DMM should be created (**V x A** in the ESM framework). This matrix models the relationships between system requirements and the *evaluation* activities conducted to assess the concepts relative to these requirements. To build this DMM, the system requirements are populated in the column headers and *evaluation* activities in the row headers. Similar to other matrices, interactions are mapped by filling in row and column intersections with "1"s. In the **V x A** DMM, the interactions between column *x* and row *y* should be interpreted as: "The system requirement *x* is evaluated through system activity *y*".

In addition to the identification of concept progression activities, the matrices built up to this point are used to transfer the clusters identified for the system functions to system objects, requirements and activities. This enables the system development team to conduct the *Concept Selection* process according to the conceptualization sequence identified in the partition analysis of the Function DSM (Figure 34 – Identifying concept layers using the Function DSM Figure 34). Using the concept progression activities identified in the **V x A** and **O x A** DMMs, an Activities DSM (**A x A**) should be created for each *concept layer*.

Activity DSMs use the format of a time-based DSM (described in 2.1.1). In the Activities DSM, input and output interactions among concept progression activities are mapped. Figure 39 shows an Activities DSM example. In this example the concept progression activity 2 requires input from activity 1 and activity 4. In addition, activity 2 provides an output to activities 4 and 6. Activities 2 and 4 are interdependent. A sequencing algorithm should be applied to this DSM to identify the sequence that maximizes a feed forward flow and the groups of activities that should be treated as interdependent. In Figure 39, the left side shows the DSM before the partition is applied and the right shows the DSM after the partition is applied.



		1	2	3	4	5	6	7	8	9	10
Activity 1	1	1			1						
Activity 2	2	1	2		1						
Activity 3	3			3							1
Activity 4	4	1	1		4						
Activity 5	5				1	5					
Activity 6	6		1				6				
Activity 7	7					1		7	1		
Activity 8	8							1	8		
Activity 9	9						1			9	
Activity 10	10									1	10

		1	2	4	5	6	7	8	9	10	3
Activity 1	1	1		1							
Activity 2	2	1	2	1							
Activity 4	4	1	1	4							
Activity 5	5			1	5						
Activity 6	6		1			6					
Activity 7	7				1		7	1			
Activity 8	8						1	8			
Activity 9	9					1			9		
Activity 10	10								1	10	
Activity 3	3									1	3

Figure 39 - Activities DSM example, before and after partition

Once the sequence of activities has been identified in the Activities DSM, the system development team should define the selection stages for each *concept layer*. This is done when the number of stages and their places in the sequence has been determined. As explained earlier, a selection stage involves a decision making process in which the set of concept alternatives is reduced based on a quantitative and a qualitative evaluation. The author recommends considering a selection stage after data has progressed from one level to the next and most value assessments have been updated to the new level of data. As a result, 2-4 selection stages will be considered for each concept layer.

5.1.2 Multi-stage concept selection

As explained earlier in this chapter, each selection stage involves a *Selection analysis* in which the stakeholders decide which concept alternative(s) will be matured in downstream activities. The *Selection analysis* considers two elements: a quantitative analysis and an assessment of the concept integrity (a qualitative evaluation). Figure 40 shows a layout of the *Selection Analysis* process.

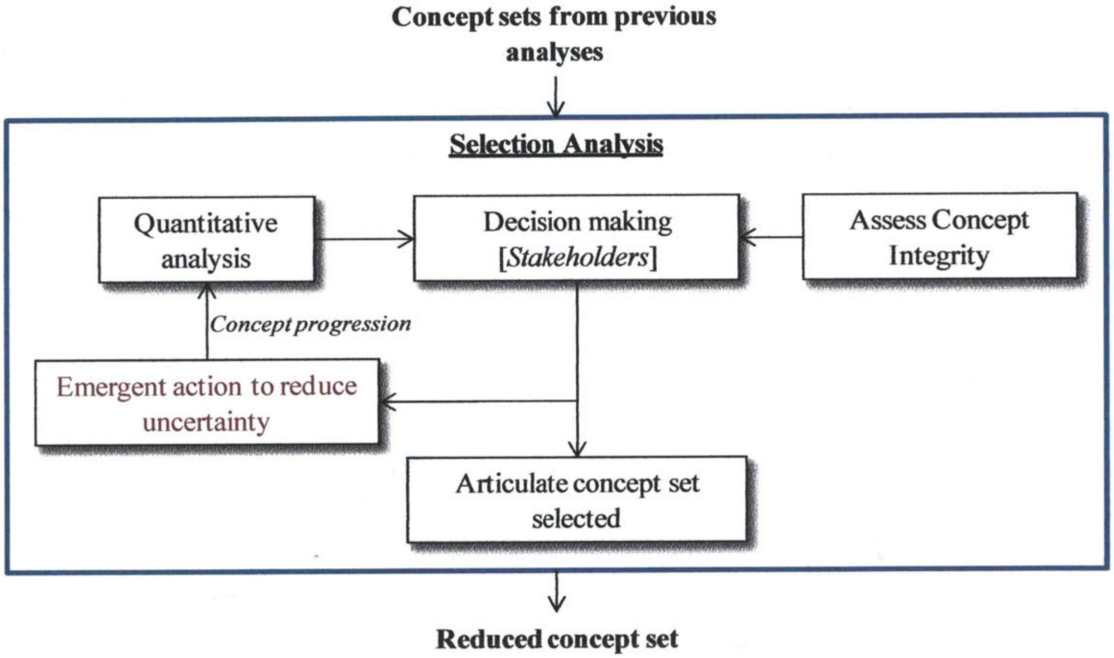


Figure 40 - Selection Analysis layout

Quantitative analysis

The quantitative analysis provides information about the performance and feasibility of the concepts in the set, relative to system requirements. This information is used to compare the value delivery of the concepts in the alternative set. To do this analysis, the first step is identification of requirements that define the *feasible region* and those that are in the *trade-off region.*

System requirements (objectives) that define the *feasible region* are those that must be satisfied to have a feasible concept. These requirements are considered satisfied when the concept achieves the related minimum acceptable performance (feasibility boundary). A special characteristic of these requirements is that performance improvements beyond the minimum acceptable performance threshold do not yield additional value to the stakeholders. Requirements classified as "Performance within boundaries" and "Discrete requirements" (discussed in 3.2.1) are likely to define the *feasible region* for the concepts in the set. Typical examples for these requirements are those derived from regulations, manufacturing or serviceability needs.

Requirements/objectives in the *trade-off region* are those that meet the following criteria:

1) Improvements in the performance metric beyond the feasibility boundary (threshold for minimum acceptable performance) yield additional value to the stakeholders. In these objectives, the stakeholders look for maximization or minimization.
2) There is a trade-off relationship with other requirements that limits the maximization or minimization of the performance metric.

In the context of Exterior Systems, requirements/objectives related to attributes such as cost, quality, appearance, weight and craftsmanship are consistently in the *trade-off region.*

The quantitative analysis proposed in this methodology involves the analysis of several metrics and indicators that assess value delivery and the uncertainty around it. One metric and one discrete indicator are proposed in the value assessment of the concept alternatives. On the other hand, two metrics are considered in the uncertainty assessment. The information generated in the quantitative analysis will be a key input to the decision making processes considered in the *Multi-stage concept selection.*

Value assessment

To assess value, this methodology uses a normalized metric and a discrete indicator. The discrete indicator qualifies the feasibility of the concept alternative. To determine the *Feasibility indicator* of a concept alternative, the first step is to measure the performance level relative to each requirement classified as "Performance within boundaries". The next step is to compare the performance measurements with its corresponding feasibility boundary (the limit used to distinguish between acceptable and non-acceptable performance). If the performance level is acceptable, the requirement is qualified as "Met". Otherwise, the requirement is qualified as "Not Met". On the other hand, requirements classified as "Discrete requirements" can be directly assessed as "Met" or "Not Met".

Once all requirements have been evaluated, the concept alternative should be qualified as "Feasible" as long as all the requirements were "Met". If one or more requirements were "Not Met", the concept alternative should be qualified as "Not Feasible".

The value delivery metric, *Normalized performance,* is focused on those requirements/objectives in the *trade-off region.* The purpose of this metric is to compare the performance of the concept alternatives in the set, relative to the requirements/objectives in the *trade-off region*; in an effort to drive concept selection. This performance metric is normalized to facilitate the use of graphic tools that help visualization of the analysis. *Normalized Performance* is a metric that can take values from 1 to 5, where the worst is 1 and the best is 5. Equations 1 and 2 show the method to calculate this metric. Equation 1 should be used for requirements/objectives to be maximized (high level is better); for example, Quality. In contrast, Equation 2 should be used for requirements/objectives to be minimized (low level is better); such as Cost.

Equation 1 – Normalized performance (for maximization objectives)

$$N_{ij} = \left[\left(\frac{x_{ij} - LV_i}{HV_i - LV_i} \right) * 4 \right] + 1$$

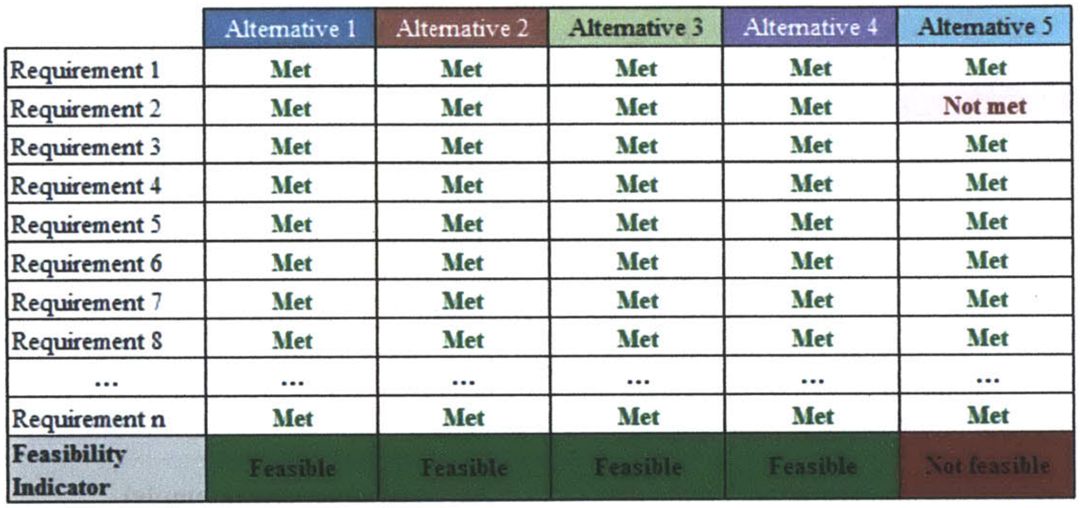
Equation 2 – Normalized performance (for minimization objectives)

$$N_{ij} = \left[\left(\frac{HV_i - x_{ij}}{HV_i - LV_i} \right) * 4 \right] + 1$$

N_{ij}**:** Normalized performance metric of concept alternative *j* related to requirement *i*.
x_{ij}**:** Performance level of concept alternative *j* related to requirement *i*.
LV_i**:** Lowest performance level in the alternative set related to requirement *i*.
HV_i**:** Highest performance level in the alternative set related to requirement *i*.

To clarify how these evaluations are conducted, the following pages show an example. Table 6 shows a *Feasibility Indicator* assessment. This table considers five concept alternatives (column headers) and *n* requirements defining the feasible region (row headers). In this example, Alternatives 1-4 were qualified *Feasible* because all the requirements were "Met". In contrast, Alternative 5 was qualified *Not Feasible* because requirement 2 was "Not Met".

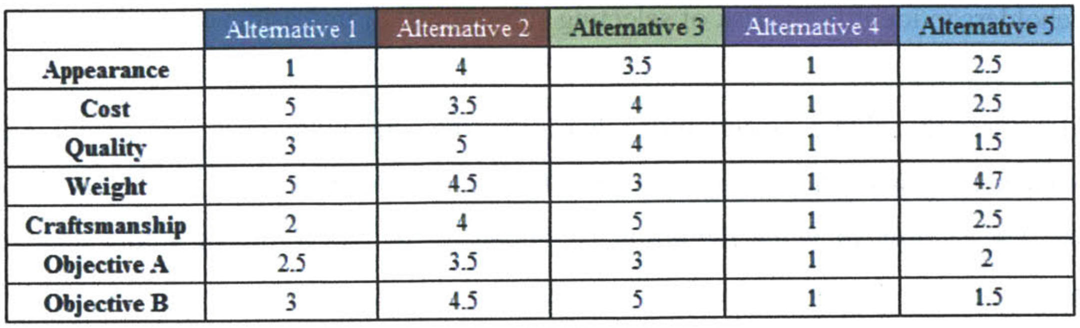
Table 6 - Feasibility indicator assessment (example)



	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Requirement 1	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 2	**Met**	**Met**	**Met**	**Met**	**Not met**
Requirement 3	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 4	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 5	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 6	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 7	**Met**	**Met**	**Met**	**Met**	**Met**
Requirement 8	**Met**	**Met**	**Met**	**Met**	**Met**
...	...	...	...	...	...
Requirement n	**Met**	**Met**	**Met**	**Met**	**Met**
Feasibility Indicator	Feasible	Feasible	Feasible	Feasible	Not feasible

Table 7 shows the summary of the *Normalized Performance* assessment for this example. The row headers in this table show the requirements/objectives in the *trade-off region*.

Table 7 - Normalized performance metrics (example)



	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Appearance	1	4	3.5	1	2.5
Cost	5	3.5	4	1	2.5
Quality	3	5	4	1	1.5
Weight	5	4.5	3	1	4.7
Craftsmanship	2	4	5	1	2.5
Objective A	2.5	3.5	3	1	2
Objective B	3	4.5	5	1	1.5

To quickly visualize the comparison among concept alternatives, the author recommends the use of a radar graph. Figure 41 shows the radar plot that corresponds to the values in Table 7. This graphic enables the system development team to quickly visualize the performance differences among the five concept alternatives relative to requirements in the *trade-off region.*

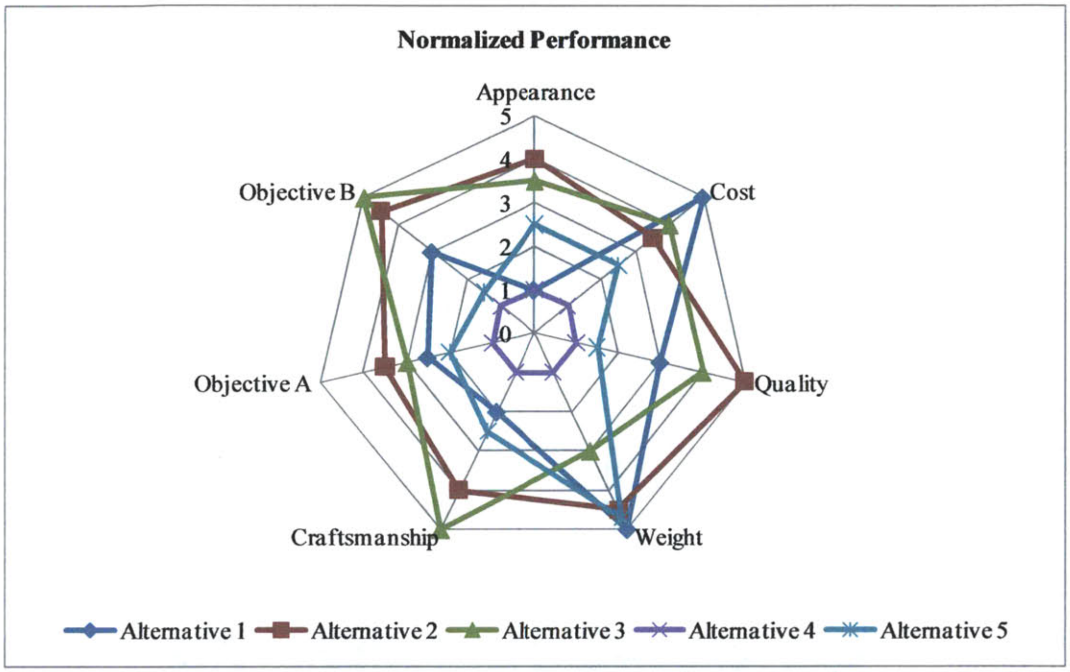


Figure 41 - Radar graph, normalized performance metrics (example)

Uncertainty assessment

In the proposed methodology, this assessment is done to quantify the amount of uncertainty in the conceptual design process. The metrics generated in this assessment are not used to identify the best concept but to estimate the likelihood of change in the evaluation of concept performance and feasibility. This information enables the stakeholders to identify the risk of selecting sub-optimal or unfeasible concepts.

As described in Table 5, uncertainties that affect the conceptual design of systems can be synthesized in two: *uncertainty in value definition* and *uncertainty in the appraisal of value*. *Uncertainty in value definition* is related to the possibility of future changes in system requirements due to changes in stakeholder preferences. This uncertainty affects the outcome of the concept selection. The concept that was originally found to be the best might become suboptimal or unfeasible after a system requirement changes. A couple examples are provided to illustrate this effect.

In the first example, consider an upgrade in a system requirement classified as *Performance within boundaries*. As explained in 3.4, these requirements are articulated as boundaries for acceptable performance. A more demanding objective can negatively affect the performance of the concept relative to other requirements because it changes the feasible region. Also, if the shift in the system requirement is large enough, the concept alternative may no longer achieve the boundary for acceptable performance and thereby become an unfeasible concept. In the second example, consider a *Theme* surface which is a system requirement classified as *Geometric Target*. Considering that many performance metrics related to Exterior Systems are related to form elements, changes in the A-surface are likely to affect the performance of the concepts and their feasibility evaluation. These two examples illustrate how the result of a concept alternative comparison can be affected after a change in system requirements. Therefore, *uncertainty in value definition* should be considered in the concept selection process.

Uncertainty in the appraisal of value refers to the possibility of future changes in the value assessment due to error. This error is a result of the interaction of the method and the data used in the value assessment (performance measurement). Low resolution in the method and/or low maturity in data derive into high levels of uncertainty. *Uncertainty in the appraisal of value* can affect the outcome of the concept selection. The result of a concept comparison based on value assessments done with a low resolution method and data with low maturity is likely to change once data matures and more accurate methods are available. The stakeholders should consider these risks in the concept selection.

In order to consider the uncertainties described above during concept selection, this methodology considers two uncertainty metrics: *Feasibility Uncertainty* and *Performance Uncertainty*. The first metric is proposed to estimate uncertainty in the *Feasibility Indicator* and the second metric to estimate the uncertainty relative the *Normalized Performance* metric.

Feasibility Uncertainty

Feasibility Uncertainty is related to requirements that define the feasible region. These requirements are affected by both ***uncertainty in value definition*** and ***uncertainty in the appraisal of value***. Therefore, the proposed metric integrates the estimates for both types of uncertainty. The *Feasibility Uncertainty* metric should be calculated for each *Feasibility Indicator*, using the probability tree described in Figure 42 and Equations 3 and 4.

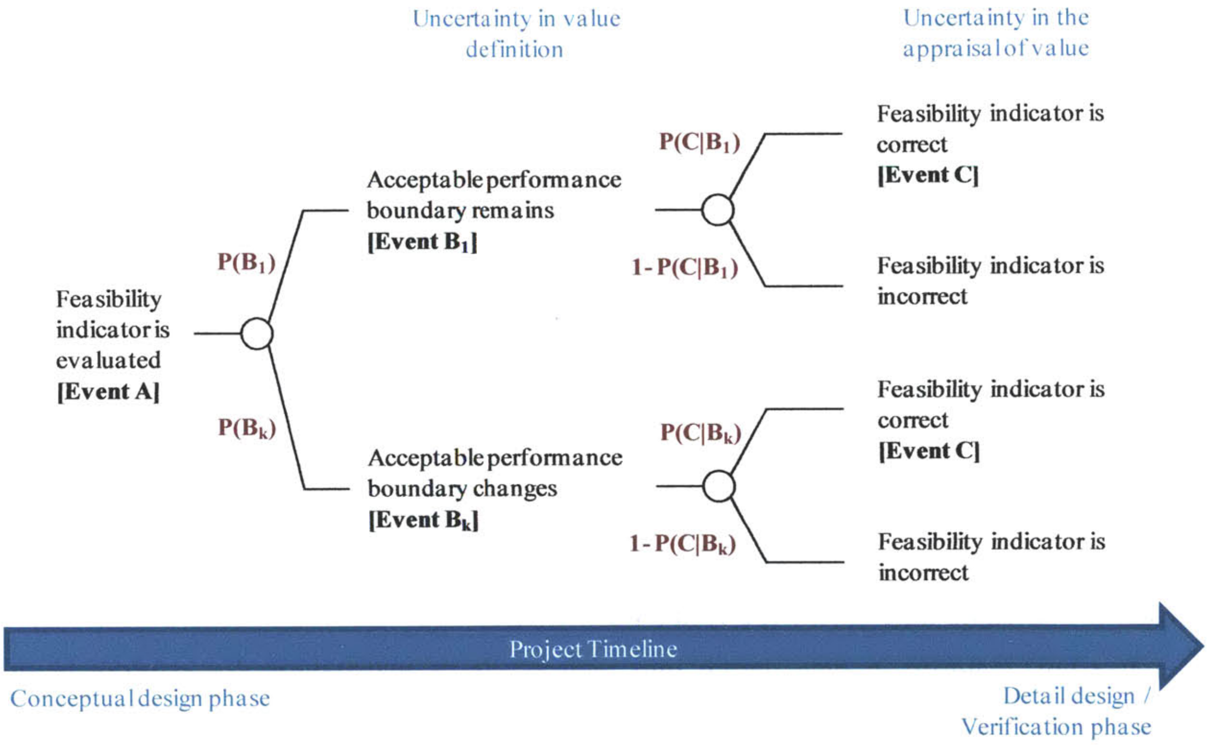


Figure 42 - Probability tree for *Feasibility uncertainty* metric

Figure notation is as follows:

Event A: Feasibility indicator is evaluated {Met, not met} during the conceptual design phase.

Event B_k: Uncertain events related to acceptable performance boundaries, for k = {1, 2… n)}

Event C: Feasibility indicator is found correct in detail design or design verification phases.

P (B_k): Probability of event B_k.

P (C): Probability of event C

P (C|B$_k$): Probability of event C, given event B$_k$.

The probability tree in Figure 42 models the uncertainty around the *Feasibility Indicator* metric throughout the development process. This model considers several events. The first (A) represents the feasibility assessment done during the conceptual design phase. As the project progresses, uncertain events that affect feasibility boundaries can occur. B_k for $k = \{1, 2, \ldots n\}$ represents these events. Finally, event C refers to the confirmation or rejection of the feasibility assessment during later phases in the PD process. *Feasibility Uncertainty* is equal to the probability of event C (Equation 3) given the probability tree in Figure 42 . Probability of even C can be calculated using Equation 4.

Equation 3 - Feasibility Uncertainty metric

$$\text{Feasibility Uncertainty} = \mathrm{P(C)}$$

Equation 4 - Probability of event C (Feasibility indicator is correct)

$$\mathrm{P(C)} = \sum_{k=1}^{n} \mathrm{P(B_k)P(C|B_k)}$$

The following example illustrates how the *Feasibility Uncertainty* metric is calculated. Consider a requirement that defines the feasible region with a boundary of acceptable performance of 45 units maximum. The performance level is found to be 35 units; therefore the *Feasibility Indicator* is considered "Met". Assume the interaction of the resolution of the assessment method and the progression level of the data has an error that has been estimated from previous projects. After applying this error to the assessment, system developers estimate that the "real" performance level is normally distributed with a mean of 35 and a standard deviation of 6. Considering this information and the feasibility boundary (45 units), it can be estimated that the probability of having a correct *Feasibility Indicator* is 95.22% (Figure 43). But, if system developers identify a 30% risk of a change in stakeholders' preferences that involves a new feasible boundary of 40, the probability of having a correct Feasibility Indicator drops to 79.77% (Figure 44).

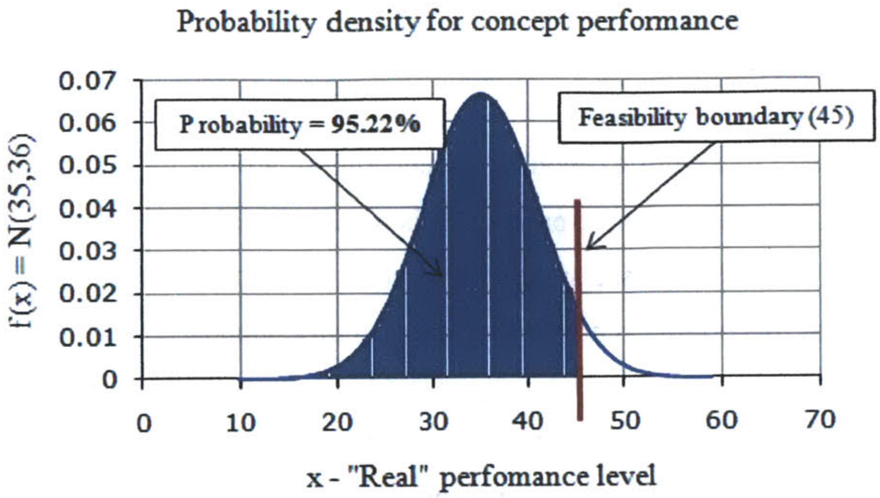


Figure 43 - Example, probability of having a correct *Feasibility Indicator*

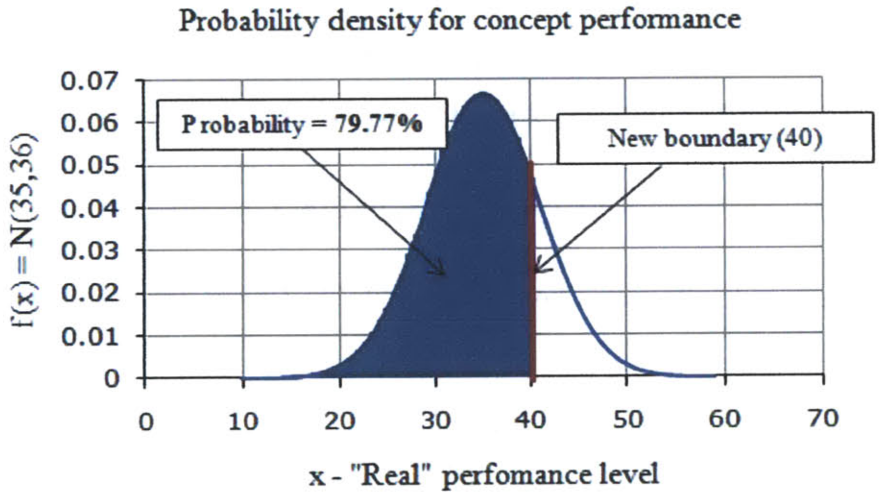


Figure 44 - Example, probability of having a correct *Feasibility Indicator* after change in the feasibility boundary

Using the information above, the following probability tree can be constructed:

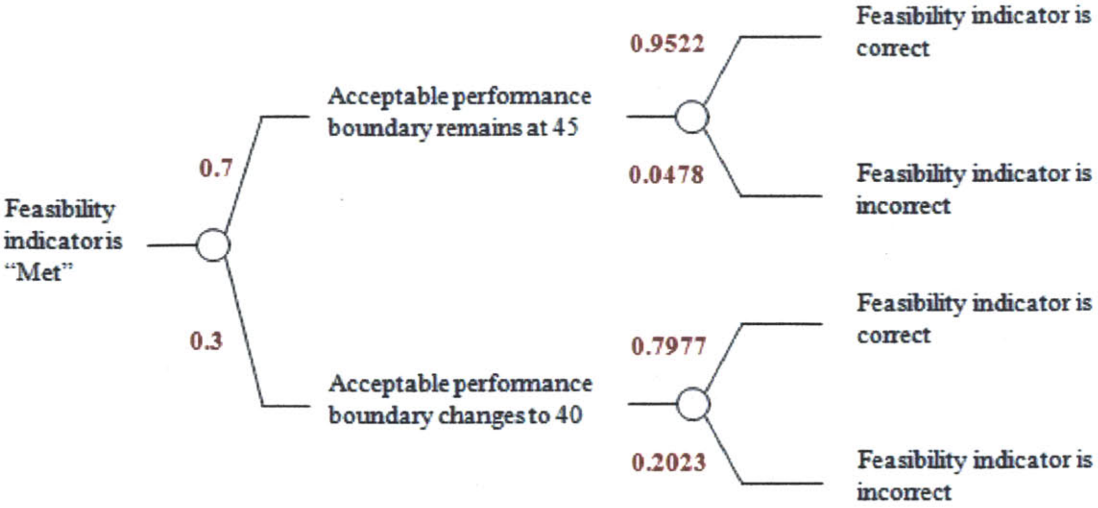


Figure 45 - Example, probability tree to calculate *Feasibility Uncertainty*

Considering the probability tree in Figure 45, the *Feasibility Uncertainty* metric is calculated in Equation 5.

Equation 5 - Example *Feasibility Uncertainty* calculation

$$Feasibility\ Uncertainty = 0.7 * 0.9522 + 0.3 * 0.7977 = 0.906$$

In the example above, the calculation of the probabilities was simple given a continuous performance metric and the availability of a probability distribution that models the *uncertainty in the appraisal of value*. But in many cases, this information is not available. In those cases, it is necessary for system developers to estimate uncertainty using less rigorous methods. In this effort, the author suggests the use of probability tables or scales to transform qualitative assessments of uncertainty to probabilities. An example of a scale to assess likelihood of events (Wilds, 2008) is shown in Figure 46.

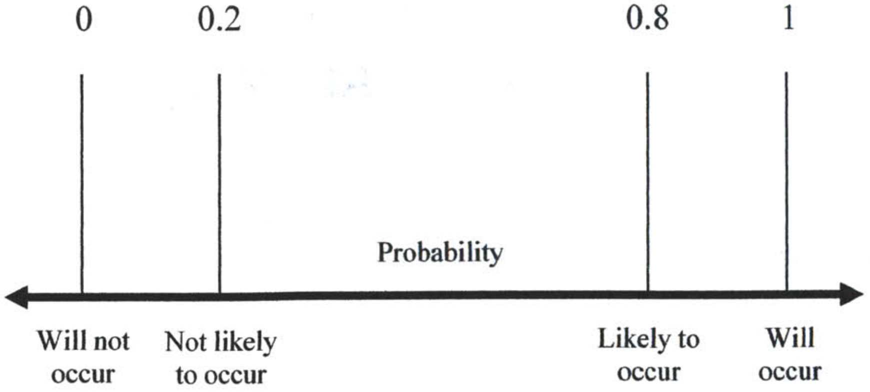


Figure 46 - Scale for assessing uncertainty in events (Wilds, 2008)

Performance Uncertainty

This metric is focused on estimating the future variation in performance metrics related to requirements in the *trade-off region. Performance Uncertainty* is the interval in which the performance level of a concept alternative is expected to be at the time of the verification phase (the "real" performance level), given a fixed probability. *Performance Uncertainty* intervals should be calculated for every objective in the *trade-off* region using a common fixed probability. The purpose of this metric is to help the stakeholders visualize how much the performance metric can change in the future and the effect of this variation in the concept comparison.

If an estimate of the probability distribution of the "real" performance level is available, the *Performance Uncertainty* interval can be calculated as a confidence interval. For example, assume a performance metric that is estimated to be normally distributed with a mean of 30 units and a standard deviation of 4. If the fixed probability (confidence level) is set to 95%, a symmetric interval for the "real" performance level is defined by a 22.16 lower boundary and a 37.84 upper boundary. Figure 47 shows the graphic interpretation of this interval.

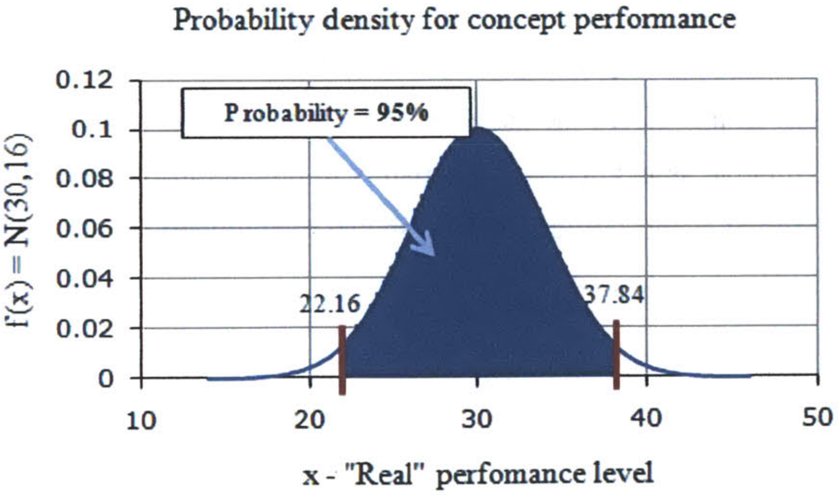


Figure 47 – Example, interval for "real" performance with 95% probability

Unfortunately, estimates of probability distributions are not always available. In novel systems and/or new methods to estimate value, there is no historic data that can be referenced to estimate a probabilistic distribution. In those cases, subject matter experts should define the *Performance Uncertainty* interval based on experience, sensitivity analyses or other forecasting methods.

After *Performance Uncertainty* intervals have been estimated for every performance metric in the *trade-off region* (for all concept alternatives), a comparison chart should be constructed for each performance metric. Figure 48 shows an example of a comparison chart. In this chart, a comparison between five concept alternatives relative to performance metric "x" is assumed. In Figure 48, the performance level estimates are plotted as histogram bars and the *Performance Uncertainty* intervals are plotted as "error bars" (in black).

In this particular example, alternative 2 is the best performing concept if considering the performance level only. But, when the *Performance Uncertainty* interval is added to the comparison, a difference between alternative 5 and alternative 2 cannot be clearly established.

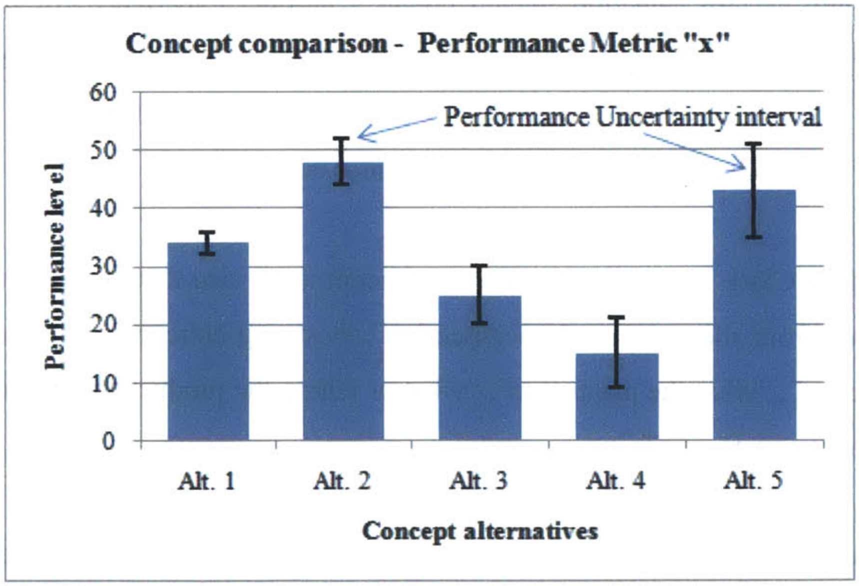


Figure 48 – Example, performance uncertainty comparison

In summary, the quantitative analysis provides a comprehensive evaluation of the concept alternatives relative to the delivery of articulated value and the uncertainty associated with this evaluation. The information generated in the quantitative analysis is a critical input for the decision making process considered in this methodology. Considering this, the metrics and indicators from this analysis were configured to enable the use of visualization tools that communicate a large amount of information in short time.

Qualitative analysis: Integrity

In addition to a quantitative evaluation, the *Selection Analysis* process involves a qualitative assessment. This element in the concept selection analysis evaluates the integrity of the concept alternatives. This analysis is conducted by internal stakeholders after being exposed to the concept alternative set, the competitive set and corporate strategies for technology, business and product.

This qualitative evaluation was inspired by the research work of Clark and Fujimoto (1990) on the connections between successful products and product development practices in the automotive industry. Clark and Fujimoto relate successful products to their *integrity*. *Product Integrity* refers to coherence between a strong product concept, the product architecture and system selection, which create a product experience for the customer. *Product Integrity* has internal and external aspects. The internal aspect is the consistency between the functions of the product and its architecture. External integrity refers to the alignment of the product performance with customer expectations.

As described by Clark and Fujimoto, strong concept is an idea that “defines the character of the product from the customer’s perspective”. A strong concept communicates “what the product does”, “what the product is”, “what or whom the product serves” and “what the product means to customers”.

In the context of automotive Exterior Systems, the concept of the product is defined during sub-processes *Theme Development* and *Compatibility Studies*, described in 3.2.2. By the time the sub-process *System Feasibility* (the focus of this methodology) starts, the concept of the product is already defined. Therefore, the integrity assessment considered in the proposed methodology is primarily focused on the internal integrity of the product.

The qualitative assessment considered in the proposed methodology is an evaluation of the consistency of the system- level concept alternatives with the following elements:

- **Product character.** System-level concepts should enforce the vision of the product created to provide the desired product experience to the customer.
- **Corporate strategies**. A system concept should be aligned with the company's strategies created to address higher level goals. One of the most important strategies for concept selection is the technology strategy. It defines the plans of the company to deploy new technologies in its products: which technologies, in which products and when. Other examples of corporate strategies that should be considered in the proposed integrity evaluation are sourcing, manufacturing and cost reduction strategies.
- **Product portfolio and brand image**. The selection of system-level concepts should be coherent with the brand message in the showroom. For example, at AOEM, system-level concepts must be compliant with a brand DNA developed to differentiate the product lineup from the competition.
- **Competitive offering**. In the qualitative assessment of the alternatives, the stakeholders should consider a comparison with competitive products. The system concept should be consistent with the intended positioning of the product relative other competitors in the segment. This element in the qualitative assessment is very important for subjective attributes like appearance and styling.

The assessment of concept integrity should be done through open discussion among the product's internal stakeholders in decision making forums.

Decision Making

The decision making process considered in this thesis is performed by the internal stakeholders of the product and led by the Chief Engineer, a high level project manager who is also the top level system integrator. During the decision making process, the stakeholders consider the results from the quantitative analysis and the conclusions from the integrity assessment of the alternative set to decide which concept(s) should continue progression.

The Chief Engineer role

Several authors have studied the Chief Engineer figure in the context of automotive product development. Clark and Fujimoto (1990) described the Chief Engineer (CE) figure as a heavyweight project manager who is the champion of the product integrity and the vigilant of the product concept. Morgan and Liker (2006) considered this leadership figure a key element in their product development framework: "The Lean Product Development System Model". Morgan and Liker described the Chief Engineer as the leader of the product development project from start to end. The CE figure is the top level system integrator who is accountable for both product and project. The authors above identified several characteristics of this role based on their observations of the processes in Japanese automotive manufacturers such as Toyota and Honda. The following summarizes the characteristics, qualities and responsibilities of the CE figure:

- **Visionary.** The Chief Engineer should be able to devise processes to create the strong product concept that will deliver the product experience to the customer.
- **Represents the voice of the customer.** The Chief Engineer should gain deep understanding of current and future needs/wants of the target customer of the product. During the entire development process, the Chief Engineer assures these needs/wants are satisfied.
- **Persuasive and with strong communication skills.** The Chief Engineer is the leader accountable for the implementation of the product concept and the integrity of the product. These responsibilities require the ability to communicate the essence of the concept to the development team and other internal stakeholders. In addition, to maintain the product integrity, this heavyweight project manager must influence the stakeholders in the decision making processes throughout concept selection.

- **Has broad knowledge of the product and the PD processes.** According to Clark and Fujimoto, the Chief Engineer must be "fluent in the languages of customers, marketers, engineers and designers". To achieve this, the Chief Engineer must have a broad knowledge of the PD process followed by the company and about the product. A Chief Engineer should have work experience in multiple aspects of the PD process.
- **Has exceptional engineering skills.** In this role, individuals are exposed to a large amount of product data. The Chief Engineer should be able to quickly process this data in order to make decisions. Strong engineering skills are required for this purpose.
- **Empowered.** In addition to the ability to influence people, a Chief Engineer must have a high rank in the organization. This allows dealing with the whole organization and enables the enforcement of assignments and decisions.
- **Focused on the product not on management.** The Chief Engineer figure is focused on product creation not on management duties. Chief Engineers have few people with a direct report line that assist in system integration duties. An interesting observation made about Chief Engineer figures in Japanese automakers was their mindset of "going to the source" to get information and address the issues. These individuals spend the majority of their time discussing the product engineers working on the product rather than attending management meetings.
- **Is a system integrator.** As stated before, the Chief Engineer is the champion of the product's integrity. This individual assures the consistency of the concept and the architecture at multiple system levels, which is a system integration task. The Chief Engineer understands relationships among the systems in the product and how these work together to deliver the product experience. In addition, the Chief Engineer is responsible for addressing conflicts and resolve tradeoff relationships. Formal System Engineering training is recommended for this role.

Guideline for decision making

The decision making process should be conducted in a dedicated forum with the attendance of all the affected stakeholders. The decision making process is a thorough discussion in which stakeholders compare the concept alternatives based on the data provided by the quantitative analysis and the integrity of the concept alternatives. This discussion should be led by the Chief Engineer who is responsible for the outcome of the decision making process.

The author suggests the following questions as a guideline for conducting the decision making process after the stakeholders have been exposed to the results of the quantitative assessment and concept integrity has been evaluated.

1) Are there any unfeasible or dominated concept alternatives?

Value assessment metrics determined during the quantitative analysis (*Feasibility Indicator* and *Normalized Performance*) can be used to quickly identify unfeasible or dominated solutions. Dominated solutions are those that are outperformed by the other concept alternatives in all *Normalized Performance* assessments. In a radar graph, dominated solutions are plotted closer to the graph center than the others. Using the Figure 41 as example, Alternative 4 is a dominated solution. Unfeasible and dominated concept alternatives are candidates to be discarded.

2) Do we have strong concepts in the alternative set?

On the opposite side of the performance spectrum, stakeholders should identify the best performers in the alternative set. This question was first applied to concept selection in Pugh's controlled convergence framework (discussed in 2.3.1). These concept alternatives are the candidates to be selected.

3) How much uncertainty remains in the alternative set? Is it likely that the quantitative analysis changes in the future?

Uncertainty metrics acquaint the stakeholders with an estimate of the likelihood of selecting a suboptimal concept (from a performance standpoint) if the concept is selected at the time of the uncertainty estimate. If uncertainty levels are high among the stronger concepts, the final concept selection should be delayed to a subsequent selection stage. On the other hand, if uncertainty is low and a strong concept has emerged, the final concept selection can be done immediately.

4) What are the trade-off relationships within each concept alternative? Can we create better concepts by recombining design solutions?

The identification of trade off relationships among the concept alternatives enables the stakeholders to identify opportunities to improve the concepts via recombination of design solutions. Recombination of design solutions to generate stronger concepts was first introduced in Pugh's method (2.3.1). This action could also help reduce the number of alternatives. For example, assume there is a set of four feasible concepts in which the stakeholders cannot identify strong concepts. If trade-off relationships are different from concept to concept, there could be an opportunity to configure two or three stronger concepts by recombining design solutions in the previous set. A key enabler for this process is the matrix-based system modeling tool proposed in this methodology. This can help the identification of relationships between design solutions and performance metrics.

5) How many concepts can the team manage in the following concept progression activities?

This is a very important query in the concept selection discussion. This question uncovers conflicts between delays in concept selection (driven by high levels of uncertainty) and the resources/time available for the upcoming concept progression activities. To identify these conflicts, the decision makers must know what the upcoming concept progression activities are and the capacity of the development group executing these activities. For the first set of information, the partitioned Activities DSM (**A x A**) enable system developers to visualize what the next concept progression activities are. For the second set of information, it is fair to assume that the affected stakeholders know how much workload can be handled in the time allotted for concept progression activities, since this workload is generally similar from project to project.

6) Do we need an emergent action to aid concept selection?

If uncertainty metrics show that concept selection should be delayed, but the resources available to execute the upcoming concept progression tasks cannot handle the workload, the stakeholders are under pressure to force concept selection. To reduce the risk of selecting a suboptimal concept, the stakeholders should consider an emergent action to reduce uncertainty in a short time period in an effort to make a more informed decision without major effects in project timing. Examples of emergent actions to reduce uncertainty are special prototypes, tests, workshops or field research (including clinics). Since these actions are not part of the regular schedule for concept progression activities, stakeholders should define clear objectives and timing for these actions.

Prototypes are a very powerful instrument to reduce uncertainty. Examples of the use of prototypes in concept selection are available in several industries. The consumer electronics industry in particular, uses prototypes extensively to quickly reduce uncertainty in concept selection (March, 1994). In another example, the consulting firm IDEO (specialized in design and innovation) considers prototyping a pillar in their design philosophy. This is illustrated in one of IDEO's innovation principles: "If a picture is worth a thousand words, a prototype is worth ten thousand" (Thomke & Nimgade, 2007). IDEO uses multiple prototypes to evaluate the concepts created during brainstorming sessions. Each prototype has the objective of evaluating a specific aspect of the concept thereby reducing its complexity and speeding up the process.

Obviously, prototyping an entire vehicle to reduce uncertainty in concept selection is out of the scope of an emergent action. But the use of system engineering concepts allow the creation of partial prototypes or "mock ups" created specifically to evaluate a particular aspect with a high level of uncertainty.

7) Which is or are the concept(s) that should continue in the process?

Once the integrity in the concept alternatives has been evaluated and questions 1-6 have been discussed, it is time to decide which concept alternative(s) should be progressed in the following phase.

5.2 System Architecture Definition

Once the multi-stage concept selection process has concluded and one concept alternative has been selected, the next major step in the conceptual design process is the definition of the system architecture. The proposed methodology considers two tasks to complete the last step in the development of the system concept.

5.2.1 Implementing countermeasures for remaining uncertainties

Before the system architecture is defined, the system development team should verify if there are still elements of uncertainty that could drive changes in the system architecture during later design phases. If so, the system development team should implement countermeasures for these uncertainties. At this stage, two uncertainty management strategies are available to the team: robustness or flexibility.

Using a robustness strategy involves designing the system so that it performs as intended even if the uncertainty unfolds. In contrast, using a flexibility strategy involves embedding features in the design that allows adaptation to the new conditions (without negative effects in the architecture) if the uncertainty materializes. The choice of the strategy to use depends on the cost, its benefit and the nature of the uncertainty.

5.2.2 Articulate System Architecture

As part of their product development framework, Ulrich and Eppinger (2008) define four steps to articulate system architecture: "Create a product schematic", "Cluster the elements of the schematic", "Create a rough geometric layout" and "Identify the fundamental and incidental interactions". In more generic terms, articulating the system architecture involves the creation of graphic representations of the architecture that clearly communicate which are the elements of the system, how these work together to perform the system functions and the interactions that exist within these elements.

In the context of our methodology to conceptualize Exterior Systems, articulating the system architecture involves the following items:

1) 3D CAD assemblies in vehicle-position with the major components of the system that show how these components are located and attached.
2) 3D CAD studies that show compliance with geometric targets and mechanism simulations.
3) An ESM model for the system.
4) Concept development documentation updated and stored for future reference.

5.3 Addressing generic and AOEM-specific conceptual design problems

As specified before, the intent of this concept development methodology is to maximize value delivery to the stakeholders and prevent the generation of waste in downstream processes. To fulfill this objective, the approach selected was the configuration of methods and tools that allow system developers to avoid the concept development problems that constrain value delivery and generate waste. This thesis research identified four classes of generic concept development problems and three that are AOEM-specific.

The methods and tools associated in the Concept Selection step were configured to prevent the occurrence of the following generic concept development problems:

- **Class II "Lack of thoroughness in concept selection".** As explained in 3.4, this problem class considers the following scenarios: omitting aspects of value and/or lack of foundation in the concept selection. The proposed methodology capitalizes on the use of the system engineering V model to gather a comprehensive list of system requirements. In addition, the matrix-based modeling tool enables one to relate these requirements to system functions, objects and activities. Furthermore, a detailed analysis (quantitative and qualitative) nurtures the discussion during the decision making process, providing a strong foundation to the concept selected by the end of the process.

- **Class III "Uncertainty is not considered in concept selection".** The metrics and indicators developed in the proposed methodology help quantification of both the uncertainty in the definition of value and the uncertainty in its appraisal. This covers all the elements of uncertainty identified in the concept development process. Uncertainty estimates identify the need for a delay in concept selection or the execution of an emergent action to reduce uncertainty thereby reducing the risk of selecting a sub-optimal concept alternative.

In addition to the above, the proposed methodology is configured to address two AOEM-specific concept development problems:

- **The functional aspect of the concept converges too quickly.** The proposed methodology concentrates on the functional aspect of Exterior Systems and considers a multi-stage concept selection process driven by uncertainty and value assessments. This process allows a gradual reduction in the number of concept alternatives while they are progressed. As explained before, the input from the styling aspect of the concept is considered a system requirement from the functional perspective. If there are high levels of uncertainty in the inputs from the *Theme*, uncertainty metrics will indicate the need for a selection delay. In practice, this will narrow the timing difference between selection of the *Theme* and selection of the functional aspect of the system concepts. This reduces the risk of rework and the risk of selecting suboptimal concept alternatives.

- **Uncertainty is not recognized case by case.** The proposed methodology evaluates the uncertainty in the definition of value and the uncertainty in the appraisal of value for every requirement in the system. Therefore, it allows estimation of the "real" levels of uncertainty in the system and can be different from project to project. The metrics from the quantitative analysis help the team adapt the concept selection process to the specific circumstances of the systems under development. This allows a concept to be selected quickly if uncertainty levels are low but allows delay if uncertainty levels are high.

5.3.1 Considerations for Class IV concept development problems

As discussed throughout Chapter 5, the concept selection process involves the execution of concept progression activities that consume time and resources. A product development project must meet both timing and budget objectives. Therefore, the amount of time and resources the project can allocate to the conceptual design phase is limited. It is expected that the workload related to the conceptual design phase is defined by the concept progression tasks and the number of concept alternatives to progress. It can be inferred that a specific allocation of time and resources has a specific capacity (maximum number of concepts that can be progressed). Class IV concept development problem "The alternative set is oversized" refers to those situations where the number of concept alternatives to progress exceeds the capacity of the development team given the resources and time allocated. As explained in Chapter 3, the Class IV concept development problem can affect the quality and completeness of the information generated during data-progression and evaluation tasks, leading to rework and errors in concept selection.

In an effort to achieve the best concept, the proposed methodology has the tendency to delay the concept selection until the levels of uncertainty are judged acceptable by the stakeholders. To counterbalance this tendency, the proposed guideline for the decision making process considers a resource discussion in which uncertainty vs. capacity issues are raised and addressed by the stakeholders via emergent actions. To enable this resource discussion, the affected stakeholders should have an estimate of their capacity in the upcoming concept progression tasks. The following recommendations are provided to estimate this capacity and manage the execution of the concept progression activities:

- For each concept progression activity identified in the **O x A** and in the **V x A** DMM matrices, the activity executor should identify a range for the number of working-hours that a single concept alternative can consume. Then, estimate the number of hours any additional concept alternative would consume. This practice would allow a quick estimation of the workload involved in an alternative set.
- The output of the analyses performed to the Activities DSMs (**A x A**) should be used to manage the sequence and timing to execute the concept progression activities. The partition analysis maximized the feed-forward flow in the sequence

and allowed the identification of interdependent tasks that should be executed together. In addition, the banding analysis helped identifying tasks that can be executed in parallel.

Chapter 5 describes the last two major steps in this methodology: Concept Selection and System Architecture Definition. Throughout the Concept Selection step, the system concept alternative set is matured and gradually downsized in a multistage selection process. Each selection stage involves a decision making processes in which quantitative and qualitative evaluations are considered. In the last step of the proposed methodology, System Architecture Definition, the system development team determines a strategy to manage the remaining elements of uncertainty. Also, the system architecture is made explicit via CAD data, the system modeling tool (ESM) and other graphic representations.

Chapter 6 – Application example: Conceptualization of the rear-end of a crossover utility vehicle

6.1 Application example overview

In order to test the methods and identify implementation issues, the proposed methodology was applied to the conceptual design of an automotive system. The system selected for this application example is the exterior rear-end of a crossover utility vehicle, currently under development at AOEM. The scope of this application example is limited to: definition of value at system-level, identification of concept layers in the system, the generation of concept alternatives for one concept layer and one selection stage for this concept layer. In order to protect AOEM's intellectual property none of the vehicle objectives are disclosed and the performance metrics shown have been normalized.

6.2 Value definition

6.2.1 Identify system boundaries

The product development project to be developed is classified as a *Platform Derivative*, which involves all-new exterior and interior systems. As explained in 4.2.1, the exterior of the vehicle in this project category is decomposed into three lower-order systems: front-end, roof/sides and rear. The rear-end system is the focus of this application example. Figure 49 shows a generic system boundary of a rear-end system in a vehicle with crossover utility (CUV) architecture. This system boundary includes Exterior Systems only (Table 3).

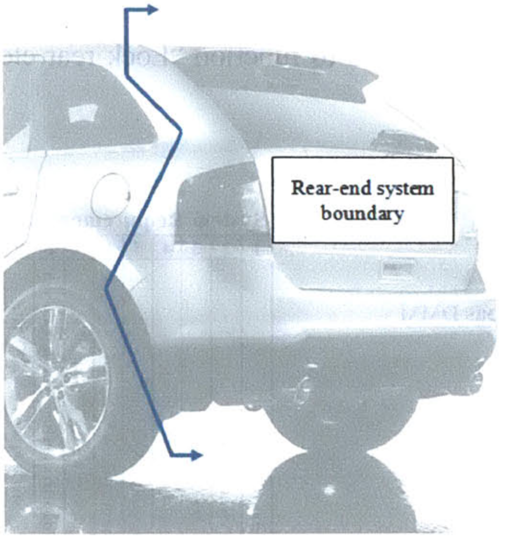


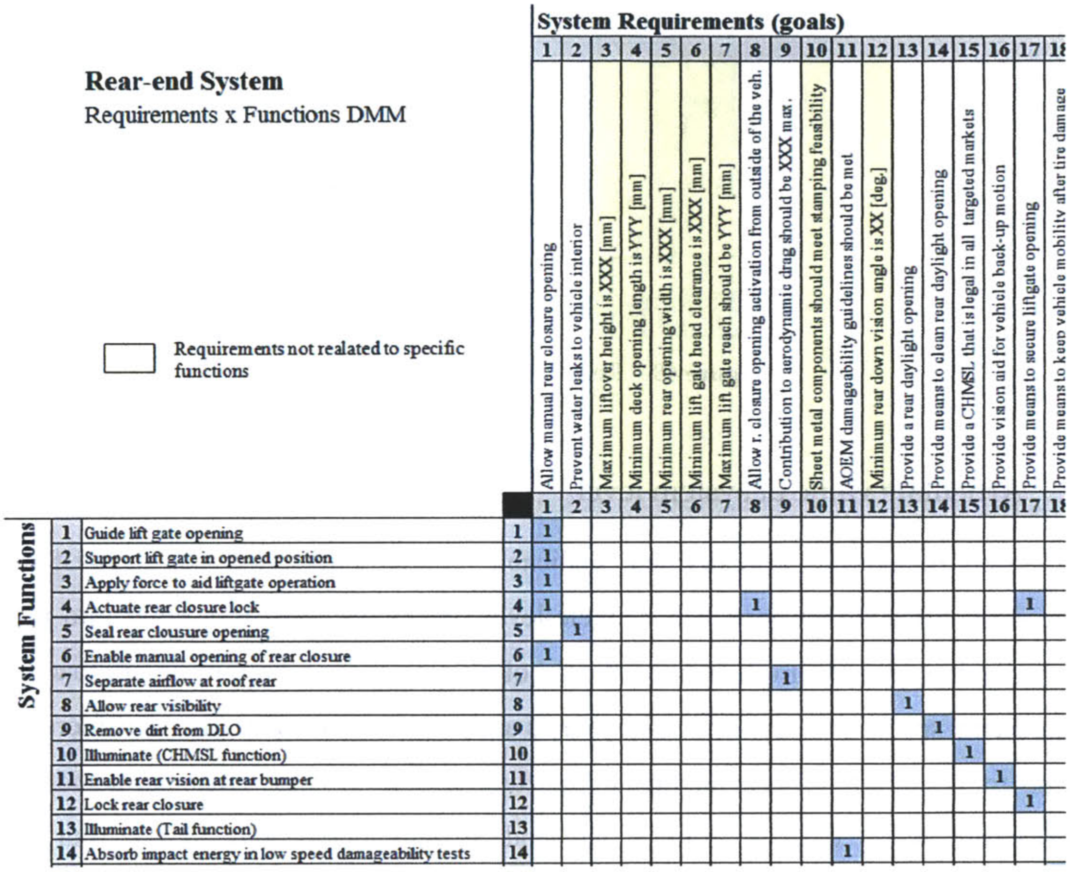
Figure 49 - Rear end system boundary

6.2.2 Articulate value at system level

After system boundaries were defined, applicable requirements to the rear-end system were gathered. In a top-down approach, vehicle-level objectives were translated into rear-end system requirements. Complementing the set of objectives, in a bottom-up approach, some requirements specific to rear-end sub-systems and components were also considered in the set due to potential impacts in the architecture of the system. Once gathered, system requirements were written from a rear-end system perspective. Fifty four system requirements were identified in this analysis. The list of system requirements is available in Appendix A.

6.2.3 Relate value to system functions

After value at system-level was articulated in 6.2.2, a Requirements x Functions DMM was constructed to identify the functions the system must perform to address system requirements. With this tool, fifty three functions were identified. Figure 50 show a fragment of the Requirements x Functions DMM (the complete matrix is available in Appendix B, Figure 64). In this analysis, there were system requirements that could not be related to any function. An example of this situation was system requirement #3 "Maximum lift over height is XXX". On the other hand, there were requirements that were related to more than one system function. For example, requirement # 17 "Provide means to secure lift gate opening" was related to function "Lock rear closure" and "Actuate rear closure lock".



Rear-end System
Requirements x Functions DMM

☐ Requirements not realated to specific functions

System Requirements (goals)

System Functions

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Allow manual rear closure opening	Prevent water leaks to vehicle interior	Maximum liftover height is XXX [mm]	Minimum deck opening length is YYY [mm]	Minimum rear opening width is XXX [mm]	Minimum lift gate head clearance is XXX [mm]	Maximum lift gate reach should be YYY [mm]	Allow r. closure opening activation from outside of the veh.	Contribution to aerodynamic drag should be XXX max.	Sheet metal components should meet stamping feasibility	AOEM damageability guidelines should be met	Minimum rear down vision angle is XX [deg.]	Provide a rear daylight opening	Provide means to clean rear daylight opening	Provide a CHMSL that is legal in all targeted markets	Provide vision aid for vehicle back-up motion	Provide means to secure liftgate opening	Provide means to keep vehicle mobility after tire damage
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Guide lift gate opening	1	1																	
2	Support lift gate in opened position	2	1																	
3	Apply force to aid liftgate operation	3	1																	
4	Actuate rear closure lock	4	1							1									1	
5	Seal rear clousure opening	5		1																
6	Enable manual opening of rear closure	6	1																	
7	Separate airflow at roof rear	7									1									
8	Allow rear visibility	8													1					
9	Remove dirt from DLO	9														1				
10	Illuminate (CHMSL function)	10															1			
11	Enable rear vision at rear bumper	11																1		
12	Lock rear closure	12																	1	
13	Illuminate (Tail function)	13																		
14	Absorb impact energy in low speed damageability tests	14											1							

Figure 50 – Requirements x Functions DMM (fragment)

6.3 Concept Generation

6.3.1 Define system concept layers

Using the system functions identified in 6.2.3, a Function DSM was constructed in order to identify functions that must be conceptualized together (concept layers) and a sequence to guide the following concept development tasks. Once built, a sequencing algorithm (partitioning) was used to cluster interdependent system functions and reorder the sequence to maximize feed-forward flow. The complete Function DSM (before being partitioned) is available in Appendix B, Figure 60. After applying the sequencing algorithm, the matrix was reordered and interdependent functions were clustered. Each cluster was considered a concept layer. As result of this analysis 13 concept layers and 6 "stand-alone" functions were identified in the rear-end system. "Stand-alone" functions are those that are outside the clusters; these functions can be conceptualized individually. Figure 51 shows the partitioned Function DSM with highlighted concept layers. A full size version of this DSM is available in Appendix B (Figure 61).

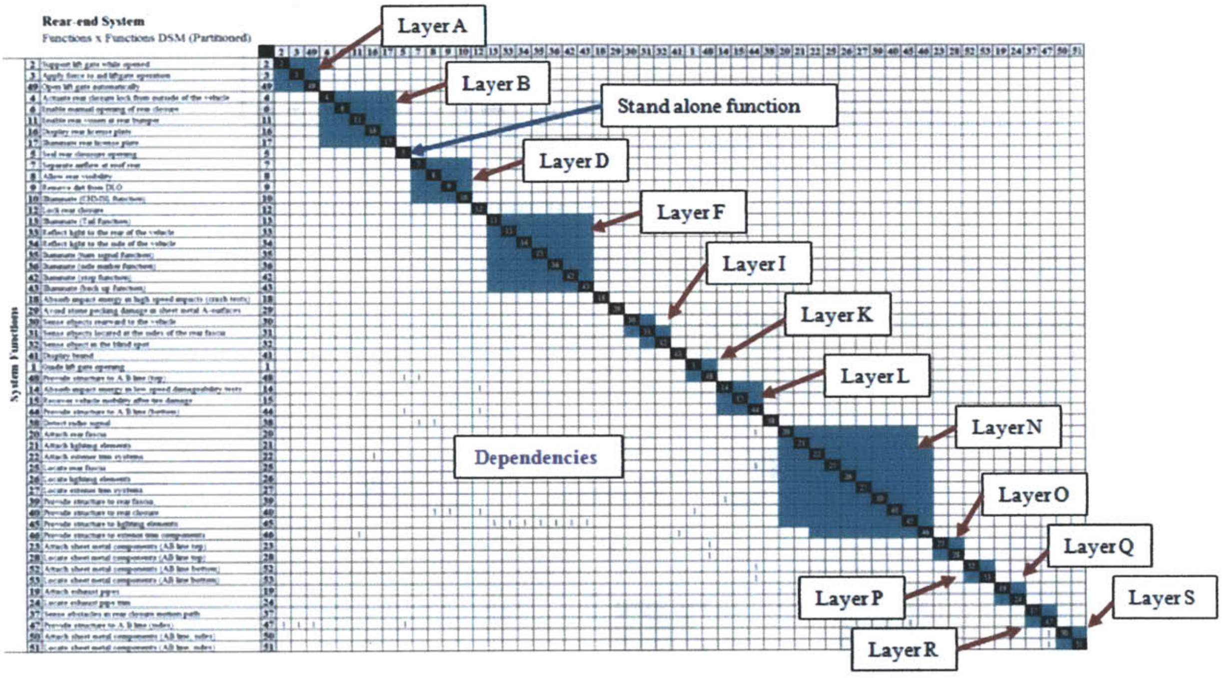


Figure 51 - Rear-end system, concept layers in partitioned Function DSM

The partitioned Function DSM allowed the identification of a sequence to conceptualize the functions of the system that maximizes feed-forward flow. For example, we can see that layers A, B, D, F, I, along with "stand-alone" functions 5, 12, 18, 29 and 41 do not have predecessors or dependency relationships outside the clusters. Therefore, these layers and functions should be the first ones to go through the next task (*configure concepts*) in parallel. In a different example, concept layer K has dependency relationships outside the cluster with function 5 and layer D (function 7). In this case, the concept alternative set for layer D and function 5 should be defined before concept layer K goes through the *configure concepts* task. The sequence identified with the partitioned Function DSM is used for concept selection as well. The following steps in the methodology are focused in concept layer D.

6.3.2 Configure concepts

Layer D clusters four system functions that should be conceptualized together. Table 8 shows concept layer D with more detail.

Table 8 - Rear-end system, concept layer D

7	**Separate airflow from vehicle**
8	**Allow rear visibility**
9	**Remove dirt from DLO**
10	**Illuminate (CHMSL function)**

Using this group of functions, a morphological matrix was configured using input from benchmarking and previous AOEM products. The morphological matrix constructed for concept layer D is shown in Figure 52.

Figure 52 - Morphological matrix, concept layer D

In the matrix above, the system functions in layer D were populated in the row headers. Each row contains a set of design solutions to address the system function in the header. Function 9 considers two rows because this function is performed with two generic objects: a wiper and a washer system. In this particular function, the wiper/washer system is a dominant concept in the industry. Therefore, the differentiation in the alternatives for this function is limited to their position on the vehicle and their construction (elements of form).

6.3.3 Define concept sets

Using the morphological matrix in Figure 52, multiple concept alternatives were configured by using different combinations of design solutions. This matrix has potential to generate 360 different combinations. After applying the proposed criteria to downsize the concept alternative set, four alternatives were pre-selected to be progressed in the concept selection tasks (Figure 53). The first criterion considered in this downsizing effort was the compatibility of the design solutions with the concept development inputs. Non-compatible design solutions were withdrawn from the combinations. For example, design alternative 4 related to function 7 ("Shape integrated to sheet metal below backlite") was discarded because it was not compatible with the styling concepts.

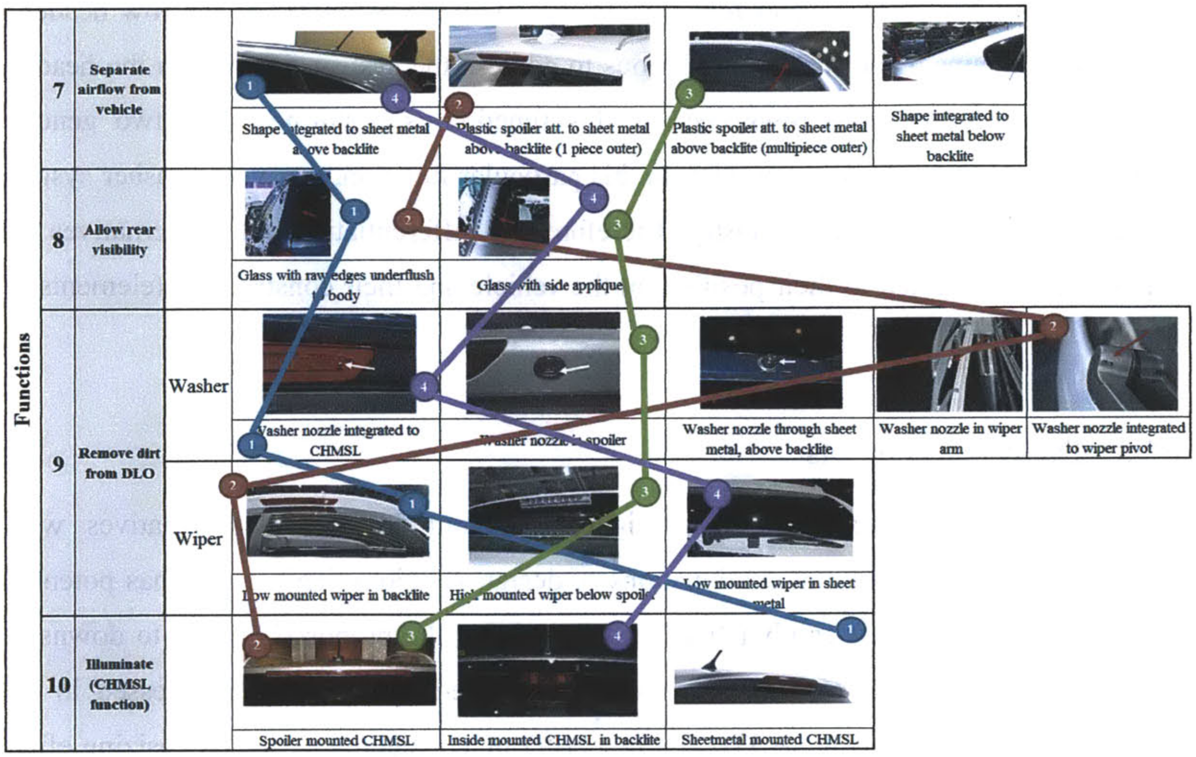
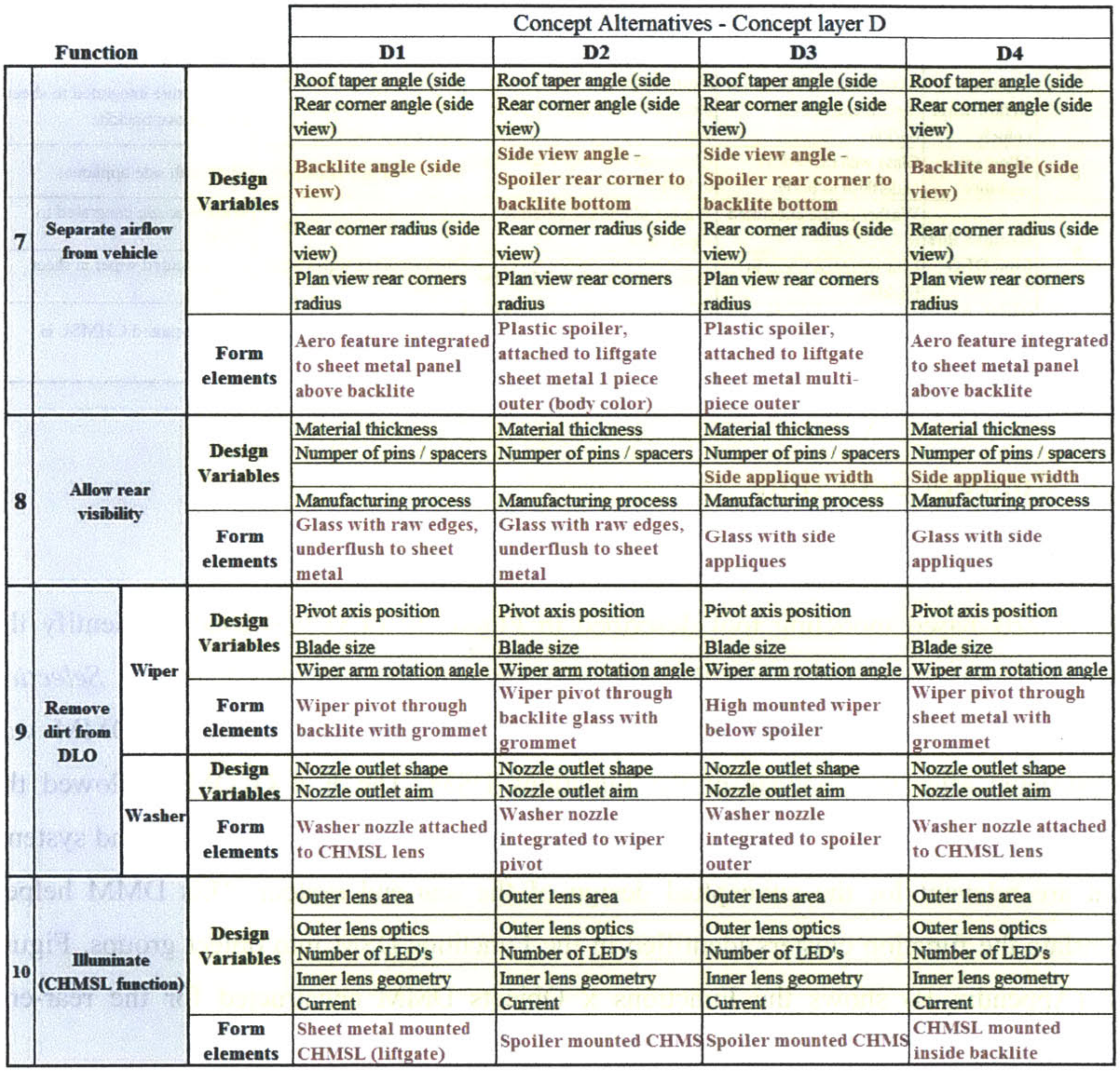


Figure 53 - Concept configuration for layer D

The second criterion considered was the differentiation of concepts. In this analysis, concept alternatives were compared relative to their design variables and elements of form. The objective here was to pre-select those compatible concept alternatives that maximize differentiation among their design variables and form elements. This allowed keeping the design space as large as possible, while reducing the number of alternatives in the set. Table 9 shows the comparison chart used to pre-select the four concept alternatives in Figure 53.

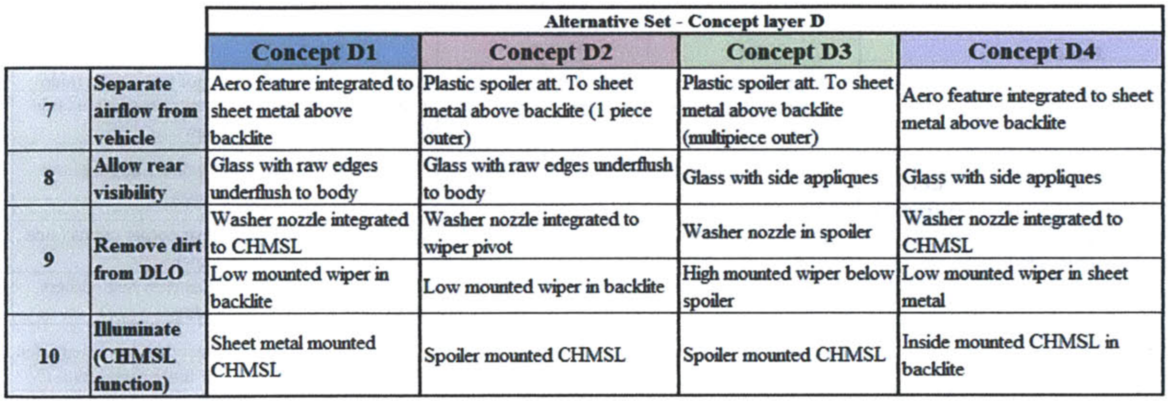
Table 9 - Concept alternatives comparison (design variables and form elements)



				Concept Alternatives - Concept layer D			
Function				**D1**	**D2**	**D3**	**D4**
7	**Separate airflow from vehicle**		**Design Variables**	Roof taper angle (side	Roof taper angle (side	Roof taper angle (side	Roof taper angle (side
				Rear corner angle (side view)	Rear corner angle (side view)	Rear corner angle (side view)	Rear corner angle (side view)
				Backlite angle (side view)	**Side view angle - Spoiler rear corner to backlite bottom**	**Side view angle - Spoiler rear corner to backlite bottom**	**Backlite angle (side view)**
				Rear corner radius (side view)	Rear corner radius (side view)	Rear corner radius (side view)	Rear corner radius (side view)
				Plan view rear corners radius	Plan view rear corners radius	Plan view rear corners radius	Plan view rear corners radius
			Form elements	**Aero feature integrated to sheet metal panel above backlite**	**Plastic spoiler, attached to liftgate sheet metal 1 piece outer (body color)**	**Plastic spoiler, attached to liftgate sheet metal multi-piece outer**	**Aero feature integrated to sheet metal panel above backlite**
8	**Allow rear visibility**		**Design Variables**	Material thickness	Material thickness	Material thickness	Material thickness
				Numper of pins / spacers	Numper of pins / spacers	Numper of pins / spacers	Numper of pins / spacers
						Side applique width	**Side applique width**
				Manufacturing process	Manufacturing process	Manufacturing process	Manufacturing process
			Form elements	**Glass with raw edges, underflush to sheet metal**	**Glass with raw edges, underflush to sheet metal**	**Glass with side appliques**	**Glass with side appliques**
9	**Remove dirt from DLO**	**Wiper**	**Design Variables**	Pivot axis position	Pivot axis position	Pivot axis position	Pivot axis position
				Blade size	Blade size	Blade size	Blade size
				Wiper arm rotation angle	Wiper arm rotation angle	Wiper arm rotation angle	Wiper arm rotation angle
			Form elements	**Wiper pivot through backlite with grommet**	**Wiper pivot through backlite glass with grommet**	**High mounted wiper below spoiler**	**Wiper pivot through sheet metal with grommet**
		Washer	**Design Variables**	Nozzle outlet shape	Nozzle outlet shape	Nozzle outlet shape	Nozzle outlet shape
				Nozzle outlet aim	Nozzle outlet aim	Nozzle outlet aim	Nozzle outlet aim
			Form elements	**Washer nozzle attached to CHMSL lens**	**Washer nozzle integrated to wiper pivot**	**Washer nozzle integrated to spoiler outer**	**Washer nozzle attached to CHMSL lens**
10	**Illuminate (CHMSL function)**		**Design Variables**	Outer lens area	Outer lens area	Outer lens area	Outer lens area
				Outer lens optics	Outer lens optics	Outer lens optics	Outer lens optics
				Number of LED's	Number of LED's	Number of LED's	Number of LED's
				Inner lens geometry	Inner lens geometry	Inner lens geometry	Inner lens geometry
				Current	Current	Current	Current
			Form elements	**Sheet metal mounted CHMSL (liftgate)**	**Spoiler mounted CHMS**	**Spoiler mounted CHMS**	**CHMSL mounted inside backlite**

In the comparison chart above, the elements that differentiate the concept alternatives are highlighted in red & bold. In this concept layer, differentiation was achieved mainly through the form elements of the concept. For example, differentiation among concept alternatives relative to function 9 was limited to their position in vehicle and mounting solutions (form elements). This indicates the use of a dominant concept (wiper & washer). Table 10 summarizes the alternative set for concept layer D after the downsizing criteria was applied:

Table 10 – Summary, alternative set for concept layer D



		Alternative Set - Concept layer D			
		Concept D1	**Concept D2**	**Concept D3**	**Concept D4**
7	**Separate airflow from vehicle**	Aero feature integrated to sheet metal above backlite	Plastic spoiler att. To sheet metal above backlite (1 piece outer)	Plastic spoiler att. To sheet metal above backlite (multipiece outer)	Aero feature integrated to sheet metal above backlite
8	**Allow rear visibility**	Glass with raw edges underflush to body	Glass with raw edges underflush to body	Glass with side appliques	Glass with side appliques
9	**Remove dirt from DLO**	Washer nozzle integrated to CHMSL	Washer nozzle integrated to wiper pivot	Washer nozzle in spoiler	Washer nozzle integrated to CHMSL
		Low mounted wiper in backlite	Low mounted wiper in backlite	High mounted wiper below spoiler	Low mounted wiper in sheet metal
10	**Illuminate (CHMSL function)**	Sheet metal mounted CHMSL	Spoiler mounted CHMSL	Spoiler mounted CHMSL	Inside mounted CHMSL in backlite

6.4 Concept Selection

6.4.1 Identify concept progression tasks and selection stages

The matrix-based modeling tool described in Figure 32 (4.3) was used to identify the concept progression tasks and the selection steps to be considered in this *Selection Analysis*. Following the sequence in Figure 42, the Functions x Objects DMM was constructed after the analysis of the Functions DSM. The **F x O** DMM allowed the identification of 42 generic Objects (lower order systems, elements of the rear-end system) that are relevant for the conceptual design of the rear-end system. This DMM helped translate the function clusters identified in the Functions DSM into object groups. Figure 62 (Appendix B) shows the Functions x Objects DMM constructed for the rear-end system.

Using the objects identified in the **F x O** DMM, the Objects x Activities (**O x A**) DMM was built. This modeling tool was used to identify the data progression activities associated with the rear-end system. Fifty eight data progression tasks were mapped in this DMM. In addition, this matrix helped classify the identified data progression tasks into three categories: Theme data progression tasks, CAD section creation and 3D CAD modeling. Figure 63 (Appendix B) shows the Objects x Activities DMM created for the rear-end system.

Considering the set of system requirements for the rear-end system, the Requirements x Activities **(V x A)** DMM was created to identify the concept evaluation activities. This DMM was used to relate the rear-end system requirements to the corresponding activities that assess concept performance. Forty eight evaluation tasks were mapped in the **V x A** DMM. In addition, these evaluation activities were classified into four categories: Theme evaluations, CAD evaluations (functional concept evaluations), CAE / Simulations and calculations. Figure 64 (Appendix B) shows the Requirements x Activities DMM configured for the rear-end system.

Using the generic objects identified in the F x O DMM and the set of system requirements considered for the rear-end system, the Objects x Requirements **(O x V)** DMM was constructed. This tool allowed mapping the relationships between objects and requirements in the system. The **O x V** DMM was used to translate the object groups into requirement groups. Figure 65 (Appendix B) shows the Objects x Requirements DMM created for the rear-end system.

The system modeling tool in Figure 32 (4.3) enabled the identification of concept layers in the system and the transfer of these groups to Objects, Requirements and Activities. The Functions DSM, the Requirements x Activities DMM and the Objects x Activities DMM, were used to construct an Activities DSM **(A x A)** to model the concept progression activities for concept layer D. The Activities DSM mapped the interactions between the concept progression tasks of concept layer D. This matrix was analyzed using a sequencing algorithm and a banding analysis.

The sequencing algorithm was applied to cluster interdependent activities and to maximize feed-forward flow in the sequence of activities. After the DSM was partitioned, sequence was scrutinized in order to identify the time frame for the concept selection stages. The outcome of this analysis was the definition of two concept selection stages. Figure 54 shows the two concept selection stages identified in the partitioned Activities DSM of concept layer D.

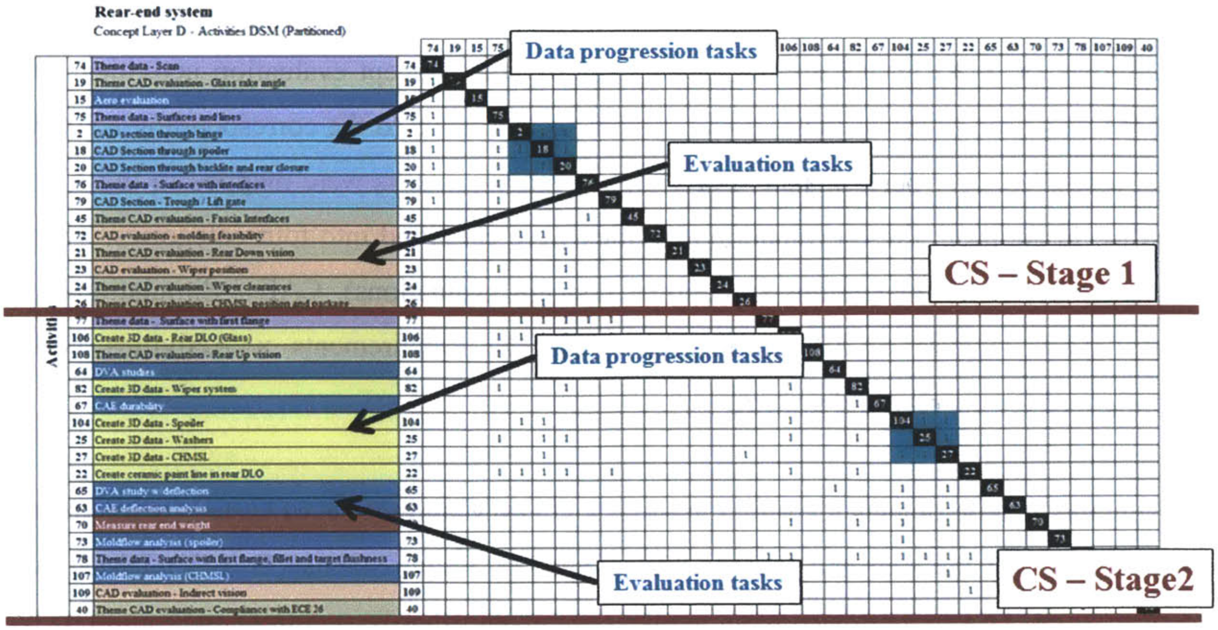
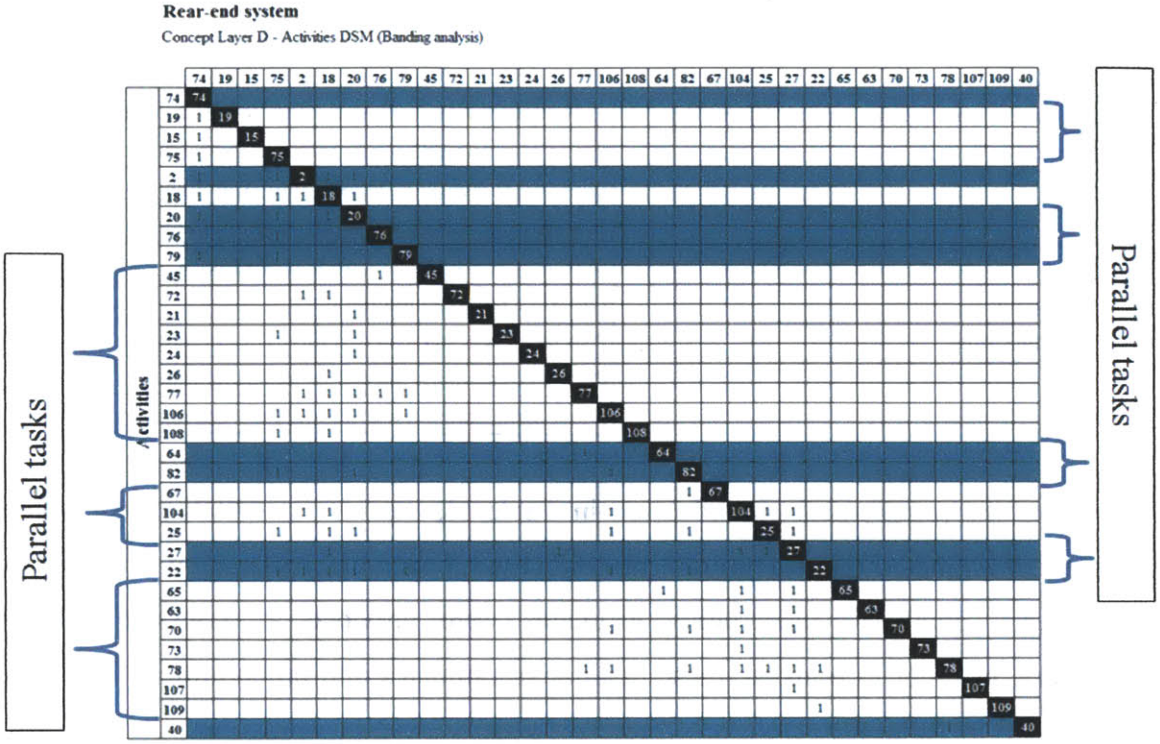


Figure 54 – Activities DSM for Concept Layer D (partitioned)

These two concept selection stages were defined based on the category and the sequence of the concept progression activities. To achieve this, a color code was used in the Activities DSM to reflect the three categories identified for data progression activities and the four categories identified for evaluation activities. As suggested in 5.1.1, a concept selection stage should be considered after data progression has advanced one level and a significant amount of the evaluations have been updated to the new data. In this application, it was determined that concept selection stage 1 for concept layer D should be considered after CAD sections were constructed and evaluated (considering the styling concept, the *Theme*).

The banding analysis was applied to the partitioned Activities DSM to find groups of tasks that can be executed in parallel. Figure 55 shows the partitioned Activities DSM after the banding analysis was performed. In this analysis rows are grouped in "bands" which are shown with alternating colors. The activities within each band can be executed in parallel.


Rear-end system

Concept Layer D - Activities DSM (Banding analysis)

	74	19	15	75	2	18	20	76	79	45	72	21	23	24	26	77	106	108	64	82	67	104	25	27	22	65	63	70	73	78	107	109	40
74	74																																
19	1	19																															
15	1		15																														
75	1			75																													
2	1			1	2	1	1																										
18	1			1	1	18	1																										
20	1			1		1	20																										
76				1				76																									
79	1			1					79																								
45								1		45																							
72					1	1					72																						
21							1					21																					
23				1			1						23																				
24							1							24																			
26						1									26																		
77					1	1	1	1	1							77																	
106				1	1	1	1		1								106																
108				1		1												108															
64																1			64														
82				1			1										1			82													
67																				1	67												
104					1	1											1					104	1	1									
25				1		1	1										1			1			25	1									
27						1									1							1	1	27									
22				1	1	1	1		1								1			1					22								
65																			1			1		1		65							
63																						1		1			63						
70																	1			1		1		1				70					
73																						1							73				
78																1	1			1		1	1	1	1					78			
107																								1							107		
109																									1							109	
40																														1			40

Figure 55 - Activities DSM for Concept Layer D (banding analysis)

6.4.2 Concept layer D - Concept selection stage 1

The application example in this chapter covers the first selection stage considered for concept layer D. The scope of this selection analysis is limited to the estimation of the metrics in the quantitative assessment.

After the number of concept selection stages was determined in 6.4.1, the Requirements x Functions DMM (**V x F**) and the Objects x Functions DMM (**O x V**) were used to identify the system requirements that concept layer D must fulfill. This subset of system requirements was classified into two groups: requirements that define the *feasible region* and requirements that are in the *trade-off region.* The summary of this classification is shown in Table 11.

Table 11 – Requirement classification for concept layer D

Requirements in the trade-off region
Appearance
Cost
Quality
Weight
Craftsmanship
Aerodynamic drag

Requirements that define the feasible region
Rear closure should meet structural guidelines
Rear end system should meet body durability
Minimum rear down vision angle is XX [deg.]
Maximum rear up vision angle is XX [deg.]
Provide a rear daylight opening
Provide means to clean rear daylight opening
Plastic components should be manufacturable
Sheet metal components should meet stamping guidelines

Considering the requirement classification in Table 11, the four quantitative assessment metrics were estimated for all requirements/objectives. Given the information available for the concepts, qualitative uncertainty estimates were provided to assess *Feasibility Uncertainty*. In order to translate these qualitative estimates into probabilities, the author used the chart in Table 12.

Table 12 – Probability chart to translate qualitative uncertainty estimates into probabilities

Probability	Qualitative uncertainty assessment
1	Certainty
0.9	Very likely
0.75	Likely
0.5	Uncertain

Tables Table 13 and Table 14 summarize the results of the quantitative assessment. Table 13 displays the estimates for metrics related to requirements/objectives in the tradeoff region. On the other hand, Table 14 shows the metrics and indicators related to requirements that define the feasible region. To interpret this data, two clarification notes are pertinent. First, *Performance uncertainty* intervals were defined by upper and lower normalized bounds. Second, the *Feasibility uncertainty* metric only considers the probabilities in Table 12.

Table 13 - Quantitative assessment for concept layer D: Objectives in the trade-off region

		D1			D2			D3			D4		
		Normalized performance	Performance uncertainty		Normalized performance	Performance uncertainty		Normalized performance	Performance uncertainty		Normalized performance	Performance uncertainty	
			Lower	Upper		Lower	Upper		Lower	Upper		Lower	Upper
Trade off region	Appearance	2	1.00	1.00	5	1.00	1.00	4	1.00	1.00	1	1.00	1.00
	Cost	5.0	0.25	0.25	1.9	0.50	0.50	1.0	0.75	0.75	4.2	0.75	0.75
	Quality	5.0	0.00	0.00	4.0	0.25	0.25	1.0	0.75	0.75	3.0	0.25	0.25
	Weight	5.0	0.25	0.25	2.4	0.25	0.25	1.0	0.50	0.50	4.1	0.25	0.25
	Craftsmanship	1.7	0.25	0.25	5.0	0.25	0.25	3.0	0.25	0.25	1.0	0.25	0.25
	Aerodynamic drag	1	0.75	0.75	4	0.75	0.75	5	0.75	0.75	3	0.75	0.75

Table 14 - Quantitative assessment for concept layer D: Objectives that define the feasible region

		D1		D2		D3		D4	
		Feasibility indicator	Feasibility uncertainty	Feasibility indicator	Feasibility uncertainty	Feasibility indicator	Feasibility uncertainty	Feasibility indicator	Feasibility uncertainty
Define feasible region	Rear closure should meet structural guidelines	**Met**	0.9	**Met**	0.9	**Met**	0.75	**Met**	0.9
	Rear end system should meet body durability	**Met**	0.9	**Met**	0.9	**Met**	0.75	**Met**	0.9
	Minimum rear down vision angle is XX [deg.]	**Met**	1	**Met**	1	**Met**	1	**Met**	1
	Maximum rear up vision angle is XX [deg.]	**Met**	1	**Met**	1	**Met**	1	**Met**	1
	Provide a rear daylight opening	**Met**	1	**Met**	1	**Met**	1	**Met**	1
	Provide means to clean rear daylight opening	**Met**	0.9	**Met**	0.75	**Met**	0.75	**Met**	0.9
	Plastic components should be manufacturable	**Met**	0.75	**Met**	0.75	**Met**	0.75	**Met**	0.75
	Sheet metal components should meet stamping guidelines	**Met**	0.75	**Met**	0.75	**Met**	0.75	**Met**	0.75

Figure 56 shows the radar plot that corresponds to the *Normalized performance* results in the table above. This chart shows that there are no dominated solutions. Furthermore, it is noticeable that concept alternatives D2 and D3 perform better in *Craftsmanship*, *Aerodynamic drag* and *Appearance*. On the other hand, concept alternatives D1 and D3 perform better in *Cost, Quality* and *Weight*.

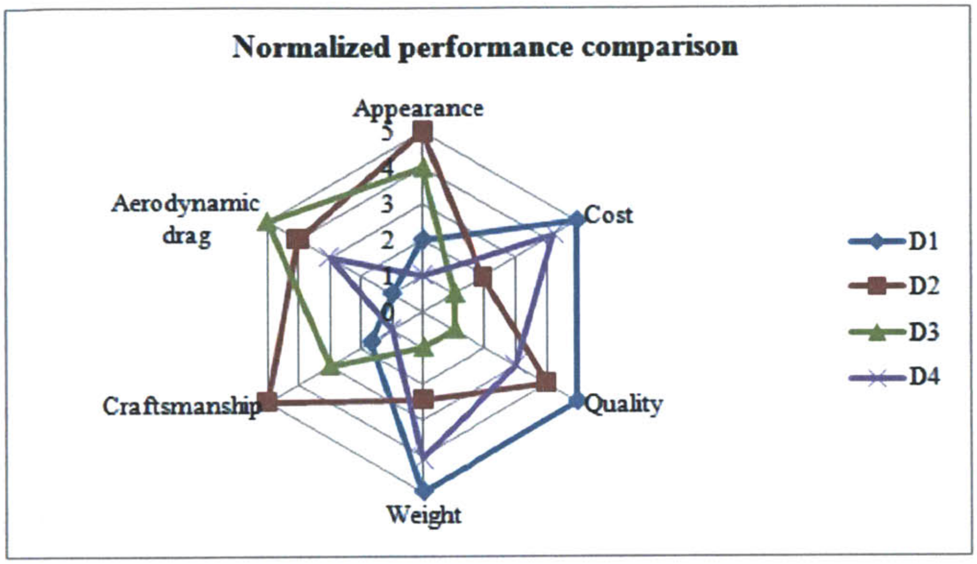


Figure 56 – Application example, Normalized Performance comparison

Performance estimates and their corresponding *Performance Uncertainty* intervals are plotted in Figure 57 and Figure 58.

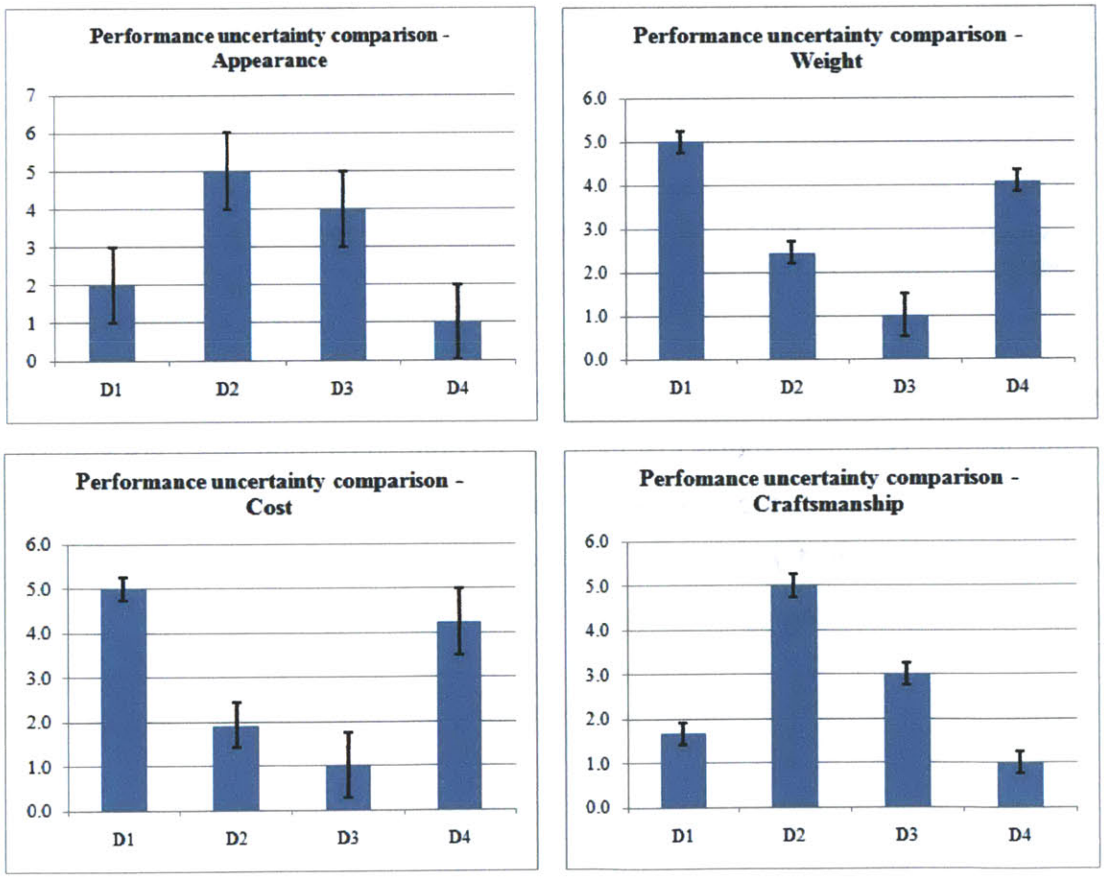


Figure 57 – Performance uncertainty comparisons per system/objective in the trade-off region (1)

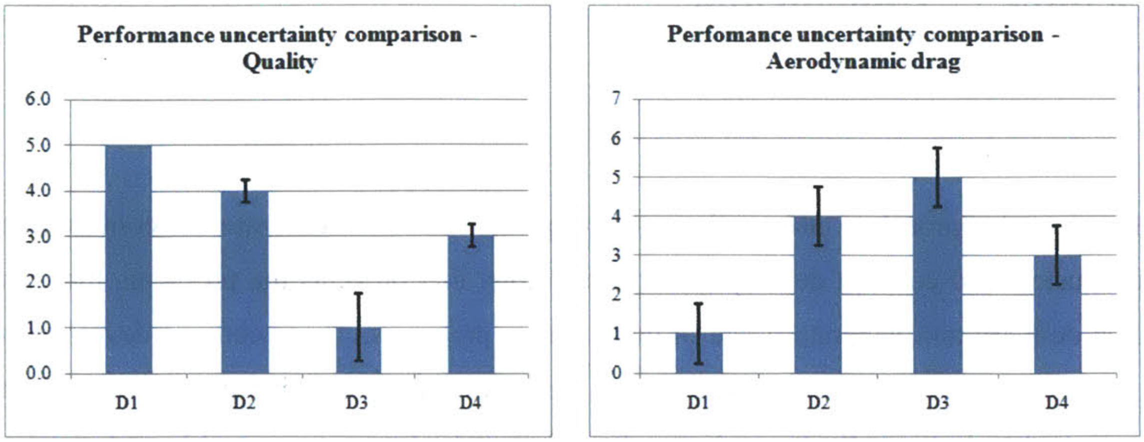


Figure 58 – Performance uncertainty comparisons per system/objective in the trade-off region (2)

Given the information provided by the quantitative assessment, the following statements summarize the status of this concept comparison:

- There are no dominated or dominating concept alternatives.
- One pair of concept alternatives delivers a better appearance / aerodynamic / craftsmanship solution while the other delivers better cost/quality and weight. Per the amount of uncertainty in the value evaluation, there is not enough information to determine the best concept.
- Concept alternative D3 involves the largest amount of uncertainty.

Considering these results, the author recommends the reduction of the concept alternative set by combining concepts D2-D3 and concepts D1-D4 in an effort to form stronger concepts prior to proceeding to the next selection stage.

Chapter 7 – Conclusions

7.1 Conclusions

7.1.1 Methodology achievements

The selected approach to address the research questions of this thesis was the configuration of a customized concept development methodology that prevents the problems that limit value delivery and generate waste in downstream processes. These concept development problems were identified in the study of the processes used by a major automotive OEM to conceptualize Exterior Systems. As result of this study, four generic problem classes and three OEM-specific problems were defined.

The proposed concept development methodology was configured based on the theory foundation provided by the literature review and the problematic identified in the OEM study. As discussed in Chapters 4 and 5, multiple mechanisms to prevent the occurrence of Class I, II and III concept development problems are formalized throughout the methodology. In addition, the proposed methodology addresses the three AOEM-specific concept development problems defined.

In addition to addressing the research questions, the proposed methodology was configured considering two high level objectives: maximization of value delivery and prevention of waste in downstream processes. The author recognizes that a rigorous proof of the fulfillment of these objectives cannot be provided within the scope of this thesis for the following reasons:

1) The qualitative assessment and the decision making process considered in the proposed methodology cannot be simulated. Any "A to B" comparison would require the application of this methodology in the conceptual design phase of two or more product development projects. In addition, value and waste would have to be monitored throughout the project. The entire process would take several years in the context of automotive PD projects.

2) A postmortem analysis of a product development project would be unable to prove improvements as the concept selection process cannot be recreated.

Nevertheless, the proposed methodology addresses a comprehensive list of concept development issues that constrain value and generate waste. As a result, the proposed methodology creates the conditions that allow value to be maximized and it prevents the waste that selection of a sub-optimal or unfeasible concept would generate.

Given the achievements summarized above, the author considers that the research questions proposed for this thesis have been thoroughly addressed.

7.1.2 Additional benefits

In addition to the enhancement of value delivery and the prevention of waste in downstream processes, the proposed concept development methodology provides further benefits. First, the tools considered in this methodology thoroughly document the conceptual design phase of a system. Given the similarities among automotive product development projects, the tools used in this methodology can be used as instruments to transfer knowledge across the organization. This would facilitate learning from previous projects.

Second, the layout of this methodology has potential to become a platform for knowledge-based automated tools. As explained in Chapter 2, morphological matrices have been used to configure automated concept generators and design repositories. In the context of automotive Exterior Systems, linking the morphological matrices to CAD templates in order to accelerate the creation of CAD data for the concept alternatives is a possibility that is well worth exploring.

7.1.3 Implementation challenges

The implementation of the proposed methodology has a few challenges to overcome. In the first place, the proposed methodology requires the organization to front load the PD process. In other words, more resources are needed in the early stages of the PD process to enable the study of multiple concept alternatives. This is a challenge in the context of AOEM because the typical approach in its process is to allocate fewer resources to the conceptualization of systems and ramp-up resources during the detail design phase. In a multi-project environment, it is quite complicated to break this inertia. Less resource limits the capacity of the team to handle multiple concept alternatives. The proposed methodology requires management to focus on increasing the number of concepts that can be handled in data progression activities. Technology is a key enabler in this effort.

Second, the proposed methodology implies paradigm changes in the evaluation of concept alternatives. The addition of uncertainty estimates (probabilities and intervals) transform punctual value comparisons into intervals, region and probability comparisons. This requires basic understanding of probability principles within the product development team, including internal stakeholders. This situation is a challenge given the multidisciplinary nature of product development teams.

7.2 Future work

Derived from this thesis, the author identified two research paths that could be considered in future work. The first research path is the configuration of a methodology that formally addresses the Class IV concept development problem "The alternative set is oversized". In order to prevent this problem, it is required that the stakeholders know the number of concept alternatives that can be handled in concept progression activities given a specific allocation of time and resources. This analysis would allow the stakeholders to accomplish an effective trade-off analysis between the risk of selecting a sub-optimal concept (due to high levels of uncertainty in the alternative set) and the risk of poor quality in the concept progression tasks (due to capacity constraints).

The second research path identified is the definition of leading indicators for the conceptual design phase that monitor the size of the design space explored and the efficiency in the concept alternative sets. Another helpful metric would be the probability of selecting the optimal concept. These metrics would enable project to project comparisons and facilitate process improvement.

Appendix A

List of system requirements considered in the analysis for this thesis.

1	Allow manual rear closure opening
2	Prevent water leaks to vehicle interior
3	Maximum liftover height is XXX [mm]
4	Minimum deck opening length is YYY [mm]
5	Minimum rear opening width is XXX [mm]
6	Minimum lift gate head clearance is XXX [mm]
7	Maximum lift gate reach should be YYY [mm]
8	Allow r. closure opening activation from outside of the veh.
9	Contribution to aerodynamic drag should be XXX max.
10	Sheet metal components should meet stamping feasibility
11	AOEM damageability guidelines should be met
12	Minimum rear down vision angle is XX [deg.]
13	Provide a rear daylight opening
14	Provide means to clean rear daylight opening
15	Provide a CHMSL that is legal in all targeted markets
16	Provide vision aid for vehicle back-up motion
17	Provide means to secure liftgate opening
18	Provide means to keep vehicle mobility after tire damage
19	Allow a legal license plate position all t. markets
20	Enable lic. plate visibility during night time (legal)
21	Maximum rear overhang is YYY [mm]
22	Meet safety requirements for rear impact modes
23	Comply with LSD requirement in truck testing
24	Achieve XXX rating in IIHS bumper evaluation
25	Meet craftsmanship targets for margins and panel flushness
26	Comply with ECE 26 for exterior projections
27	Ground clearance should be YYY [mm] minimum

28	Minimum departure should be XX [deg.]
29	Accommodate exhaust pipe integrated to fascia
30	Stone pecking damage should meet design guidelines
31	Provide auto-park feature
32	Provide audible back-up aid
33	Provide legal and competitive lighting tail function
34	Provide legal rear reflex function
35	Lighting systems should be serviceable
36	Provide legal turn signal function
37	Provide legal side marker function
38	Provide legal side reflex function
39	Enable vehicle recovery
40	Allow tie down features for transportation
41	Display brand
42	Reduce human effort to open/close the r. closure (man. Sys.)
43	Provide powered opening for r. closure
44	Avoid trapping objects when closing the r. closure (p. sys)
45	Allow radio reception
46	Plastic components should meet firm feel guidelines
47	Rear closure should meet structural guidelines
48	Rear systems should meet weight targets
49	Provide means to notice vehicles in the driver's blind spot
50	Provide legal lighting stop function
51	Provide legal lighting back up function
52	AB Line should meet structural guidelines
53	Rear end system should meet body durability
54	Plastic components must be manufacturable

Appendix B

Figure 59 – Application example, Requirements x Functions DMM

Rear-end System

Requirements x Functions DMM

☐ Requirements not realated to specific functions

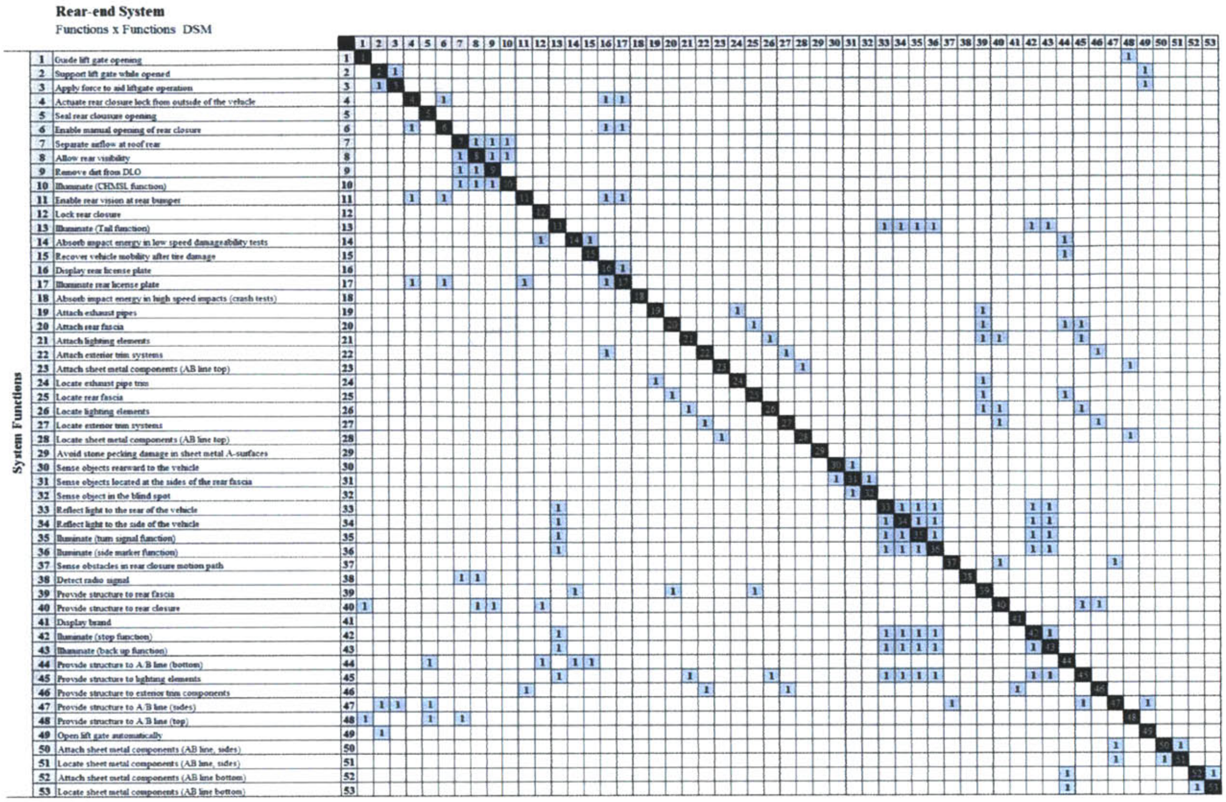
System Requirements (goals)

System Functions

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
			Allow manual rear closure opening	Prevent water leaks to vehicle interior	Maximum liftover height is XXX [mm]	Minimum deck opening length is YYY [mm]	Minimum rear opening width is XXX [mm]	Minimum lift gate head clearance is XXX [mm]	Maximum lift gate reach should be YYY [mm]	Allow r. closure opening activation from outside of the veh.	Contribution to aerodynamic drag should be XXX max.	Sheet metal components should meet stamping feasibility	ADEM damageability guidelines should be met	Minimum rear down vision angle is XX [deg.]	Provide a rear daylight opening	Provide means to clean rear daylight opening	Provide a CHMSL that is legal in all targeted markets	Provide vision aid for vehicle back-up motion	Provide means to secure liftgate opening	Provide means to keep vehicle mobility after tire damage	Allow a legal license plate position all t. markets	Enable lic. plate visibility during night time (legal)	Maximum rear overhang is YYY [mm]	Meet safety requirements for rear impact modes	Comply with LSD requirement in truck testing	Achieve XXX rating in IIHS bumper evaluation	Meet craftmanship targets for margins and panel flushness	Comply with ECE 26 for exterior projections	Ground clearance should be YYY [mm] minimum	Minimum departure should be XX [deg.]	Accommodate exhaust pipe integrated to fascia	Stone peaking damage should meet design guidelines	Provide auto-park feature	Provide audible back-up aid	Provide legal and competitive lighting tail function	Provide legal rear reflex function	Lighting systems should be serviceable	Provide legal turn signal function	Provide legal side marker function	Provide legal side reflex function	Enable vehicle recovery	Allow tie down features for transportation	Display brand	Reduce human effort to open/close the r. closure (man. Sys.)	Provide powered opening for r. closure	Avoid trapping objects when closing the r. closure (p. sys)	Allow radio reception	Plastic components should meet firm feel guidelines	Rear closure should meet structural guidelines	Rear systems should meet weight targets	Provide means to notice vehicles in the driver's blind spot	Provide legal lighting stop function	Provide legal lighting back up function	AB Line should meet structural guidelines	Rear end system should meet body durability	Plastic components must be manufacturable
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
1	Guide lift gate opening	1	1																																										1												
2	Support lift gate in opened position	2	1																																										1												
3	Apply force to aid liftgate operation	3	1																																									1													
4	Actuate rear closure lock	4 |1|					|1|								|1|																																						
5	Seal rear clousure opening	5	|1|																																																				
6	Enable manual opening of rear closure	6 |1|																																																					
7	Separate airflow at roof rear	7									1																																													
8	Allow rear visibility	8													1																																								
9	Remove dirt from DLO	9														1																																							
10	Illuminate (CHMSL function)	10															1																																						
11	Enable rear vision at rear bumper	11																1																																						
12	Lock rear closure	12																	1																																					
13	Illuminate (Tail function)	13																																|1|																					
14	Absorb impact energy in low speed damageability tests	14										|1|											|1|1|																															
15	Recover vehicle mobility after tire damage	15																	|1|																																				
16	Display rear license plate	16																		|1|																																			
17	Illuminate rear license plate	17																			|1|																																		
18	Absorb impact energy in high speed impacts (crash tests)	18																					|1|																																
19	Attach exhaust pipes	19																												|1|																									
20	Attach rear fascia	20																																													1								
21	Attach lighting elements	21																																													1								
22	Attach exterior trim systems	22																																													1								
23	Attach sheet metal components (AB line top)	23																																																			1		
24	Locate exhaust pipe trim	24																								|1|																													
25	Locate rear fascia	25																								|1|																													
26	Locate lighting elements	26																								|1|																													
27	Locate exterior trim systems	27																								|1|																													
28	Locate sheet metal components (AB line top)	28																								|1|																													
29	Avoid stone pecking damage in sheet metal A-surfaces	29																													|1|																								
30	Sense objects rearward to the vehicle	30																																1																						
31	Sense objects located at the sides of the rear fascia	31																															1																							
32	Sense object in the blind spot	32																																																	1					
33	Reflect light to the rear of the vehicle	33																																		1																				
34	Reflect light to the side of the vehicle	34																																						1																
35	Illuminate (turn signal function)	35																																				1																		
36	Illuminate (side marker function)	36																																					1																	
37	Sense obstacles in rear closure motion path	37																																											1										
38	Detect radio signal	38																																												1									
39	Provide structure to rear fascia	39																																													1								
40	Provide structure to rear closure	40																																														1							
41	Display brand	41																																								1													
42	Illuminate (stop function)	42																																																	1				
43	Illuminate (back up function)	43																																																		1			
44	Provide structure to A/B line (bottom)	44																						1																															1		
45	Provide structure to lighting elements	45																																													1								
46	Provide structure to exterior trim components	46																																													1								
47	Provide structure to A/B line (sides)	47																						1																															1		
48	Provide structure to A/B line (top)	48																						1																															1		
49	Open lift gate automatically	49																																										1											
50	Attach sheet metal components (AB line, sides)	50																																																			1		
51	Locate sheet metal components (AB line, sides)	51																								|1|																													
52	Attach sheet metal components (AB line bottom)	52																																																			1		
53	Locate sheet metal components (AB line bottom)	53																								|1|																													

* A 11” x 17” version of this matrix is available in the electronic copy of this thesis.

Figure 60 – Application example – Functions x Functions DSM



Rear-end System

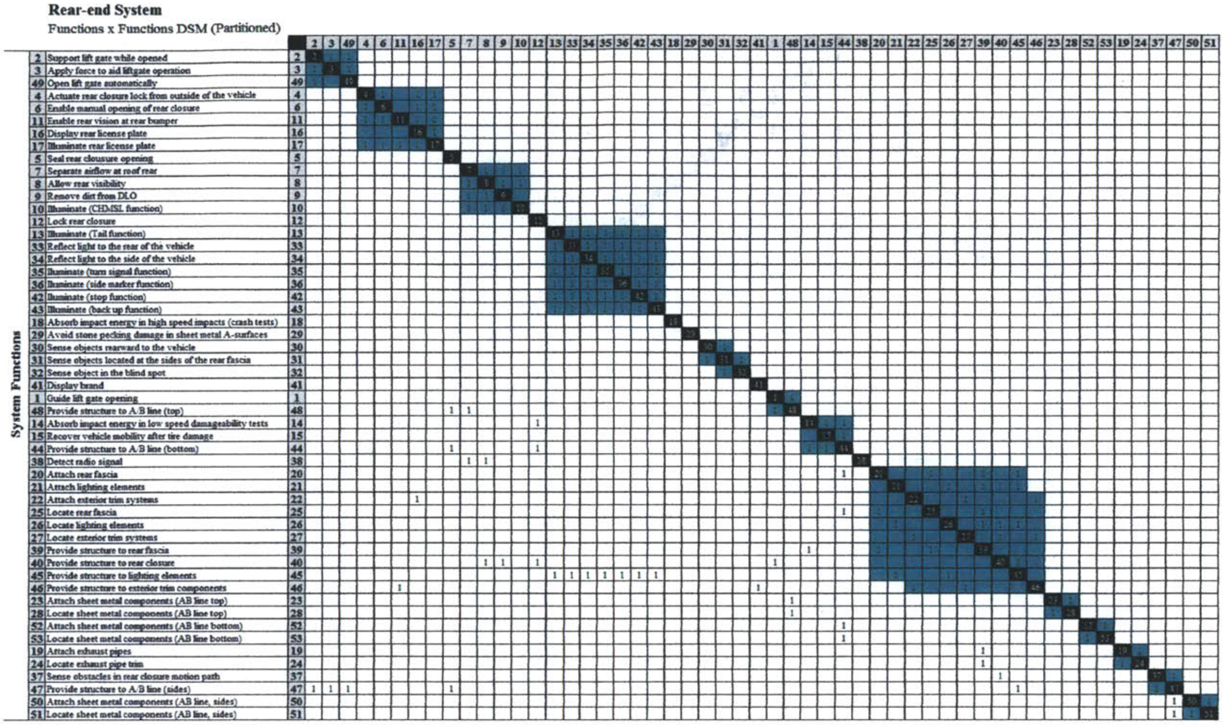
Functions x Functions DSM

System Functions

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
1	Guide lift gate opening	1	1																																													1					
2	Support lift gate while opened	2		2	1																																											1				
3	Apply force to aid liftgate operation	3		1	3																																											1				
4	Actuate rear closure lock from outside of the vehicle	4				4		1										1	1																																				
5	Seal rear clousure opening	5					5																																																	
6	Enable manual opening of rear closure	6				1		6										1	1																																				
7	Separate airflow at roof rear	7							7	1	1	1																																											
8	Allow rear visibility	8							1	8	1	1																																											
9	Remove dirt from DLO	9							1	1	9																																												
10	Illuminate (CHMSL function)	10							1	1	1	10																																											
11	Enable rear vision at rear bumper	11				1		1					11					1	1																																				
12	Lock rear closure	12												12																																										
13	Illuminate (Tail function)	13													13																					1	1	1	1						1	1										
14	Absorb impact energy in low speed damageability tests	14												1		14	1																														1									
15	Recover vehicle mobility after tire damage	15															15																														1									
16	Display rear license plate	16																16	1																																				
17	Illuminate rear license plate	17				1		1					1					1	17																																				
18	Absorb impact energy in high speed impacts (crash tests)	18																		18																																			
19	Attach exhaust pipes	19																			19					1															1														
20	Attach rear fascia	20																				20					1														1					1	1								
21	Attach lighting elements	21																					21					1													1	1					1								
22	Attach exterior trim systems	22																1						22					1																				1							
23	Attach sheet metal components (AB line top)	23																							23					1																				1					
24	Locate exhaust pipe trim	24																			1					24															1														
25	Locate rear fascia	25																				1					25														1					1									
26	Locate lighting elements	26																					1					26													1	1					1								
27	Locate exterior trim systems	27																						1					27													1						1							
28	Locate sheet metal components (AB line top)	28																							1					28																				1					
29	Avoid stone pecking damage in sheet metal A-surfaces	29																													29																								
30	Sense objects rearward to the vehicle	30																														30	1																						
31	Sense objects located at the sides of the rear fascia	31																														1	31	1																					
32	Sense object in the blind spot	32																															1	32																					
33	Reflect light to the rear of the vehicle	33													1																					33	1	1	1						1	1										
34	Reflect light to the side of the vehicle	34													1																					1	34	1	1						1	1										
35	Illuminate (turn signal function)	35													1																					1	1	35	1						1	1										
36	Illuminate (side marker function)	36													1																					1	1	1	36						1	1										
37	Sense obstacles in rear closure motion path	37																																					37			1							1						
38	Detect radio signal	38							1	1																															38															
39	Provide structure to rear fascia	39														1						1					1														39														
40	Provide structure to rear closure	40	1							1	1			1																												40					1	1							
41	Display brand	41																																									41												
42	Illuminate (stop function)	42													1																					1	1	1	1						42	1										
43	Illuminate (back up function)	43													1																					1	1	1	1						1	43										
44	Provide structure to A/B line (bottom)	44					1							1		1	1																														44									
45	Provide structure to lighting elements	45													1								1					1							1	1	1	1						1	1		45								
46	Provide structure to exterior trim components	46											1											1					1														1					46							
47	Provide structure to A/B line (sides)	47		1	1		1																																1								1		47		1				
48	Provide structure to A/B line (top)	48	1				1		1																																											48					
49	Open lift gate automatically	49		1																																																49				
50	Attach sheet metal components (AB line, sides)	50																																														1			50	1		
51	Locate sheet metal components (AB line, sides)	51																																														1			1	51		
52	Attach sheet metal components (AB line bottom)	52																																											1								52	1
53	Locate sheet metal components (AB line bottom)	53																																											1								1	53

* A 11" x 17" version of this matrix is available in the electronic copy of this thesis.

Figure 61 - Application example - Partitioned Functions x Functions DSM



Rear-end System

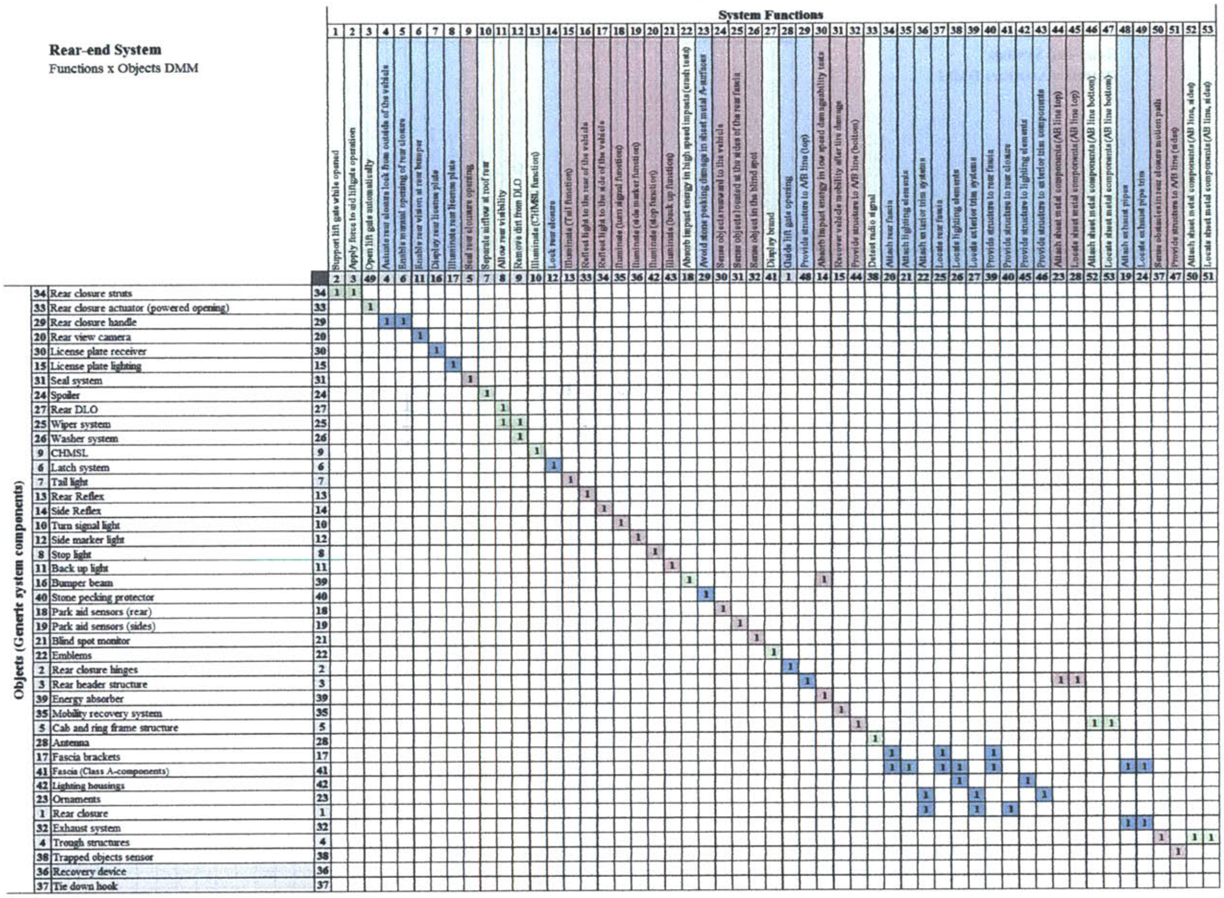
Functions x Functions DSM (Partitioned)

System Functions

2	Support lift gate while opened
3	Apply force to aid liftgate operation
49	Open lift gate automatically
4	Actuate rear closure lock from outside of the vehicle
6	Enable manual opening of rear closure
11	Enable rear vision at rear bumper
16	Display rear license plate
17	Illuminate rear license plate
5	Seal rear clousure opening
7	Separate airflow at roof rear
8	Allow rear visibility
9	Remove dirt from DLO
10	Illuminate (CHMSL function)
12	Lock rear closure
13	Illuminate (Tail function)
33	Reflect light to the rear of the vehicle
34	Reflect light to the side of the vehicle
35	Illuminate (turn signal function)
36	Illuminate (side marker function)
42	Illuminate (stop function)
43	Illuminate (back up function)
18	Absorb impact energy in high speed impacts (crash tests)
29	Avoid stone pecking damage in sheet metal A-surfaces
30	Sense objects rearward to the vehicle
31	Sense objects located at the sides of the rear fascia
32	Sense object in the blind spot
41	Display brand
1	Guide lift gate opening
48	Provide structure to A/B line (top)
14	Absorb impact energy in low speed damageability tests
15	Recover vehicle mobility after tire damage
44	Provide structure to A/B line (bottom)
38	Detect radio signal
20	Attach rear fascia
21	Attach lighting elements
22	Attach exterior trim systems
25	Locate rear fascia
26	Locate lighting elements
27	Locate exterior trim systems
39	Provide structure to rear fascia
40	Provide structure to rear closure
45	Provide structure to lighting elements
46	Provide structure to exterior trim components
23	Attach sheet metal components (AB line top)
28	Locate sheet metal components (AB line top)
52	Attach sheet metal components (AB line bottom)
53	Locate sheet metal components (AB line bottom)
19	Attach exhaust pipes
24	Locate exhaust pipe trim
37	Sense obstacles in rear closure motion path
47	Provide structure to A/B line (sides)
50	Attach sheet metal components (AB line, sides)
51	Locate sheet metal components (AB line, sides)

* A 11" x 17" version of this matrix is available in the electronic copy of this thesis.

Figure 62 - Application example, Functions x Objects DMM



Rear-end System
Functions x Objects DMM

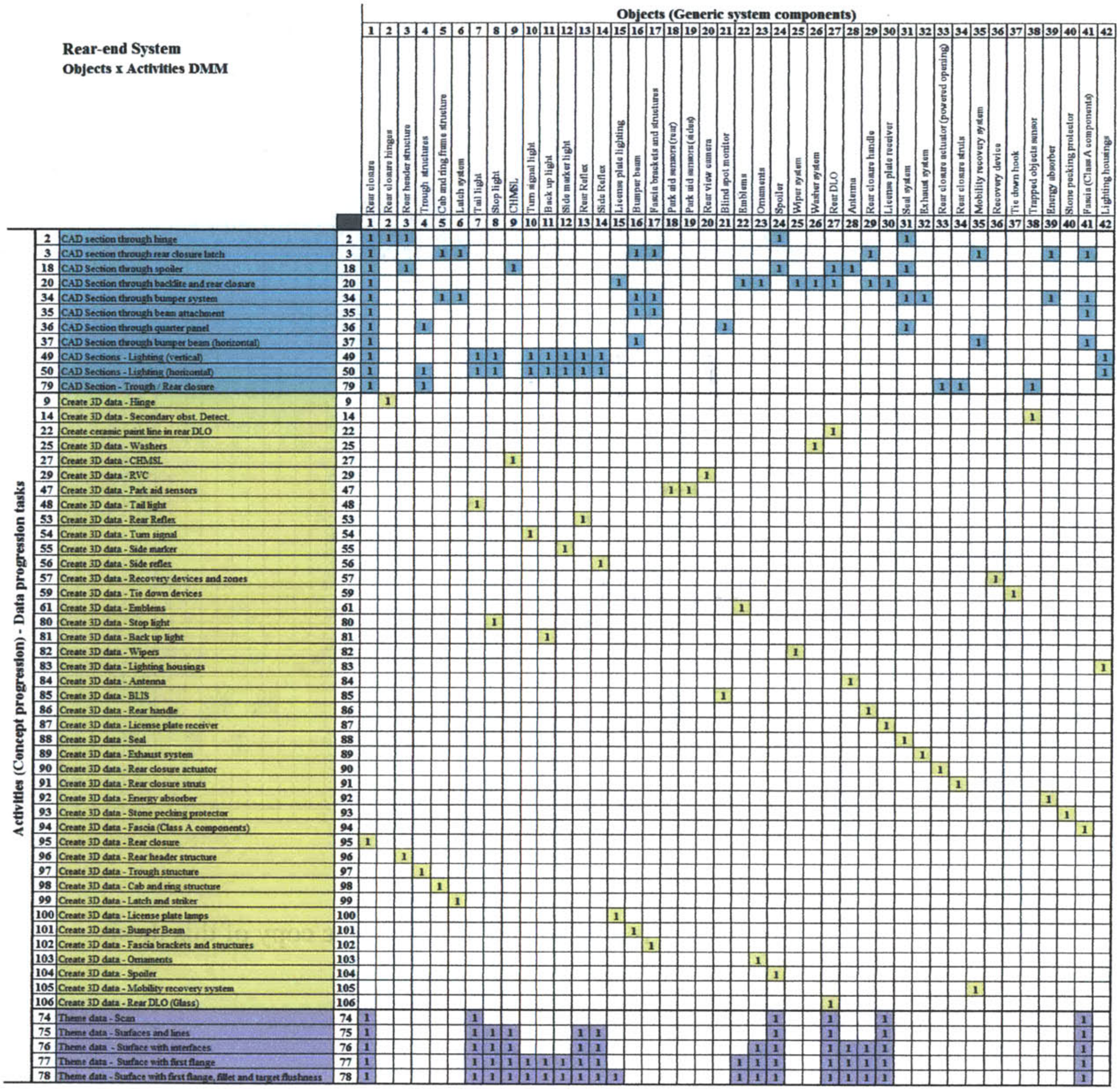
System Functions

Objects (Generic system components)

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
			Support lift gate while opened	Apply force to aid liftgate operation	Open lift gate automatically	Actuate rear closure lock from outside of the vehicle	Enable manual opening of rear closure	Enable rear vision at rear bumper	Display rear license plate	Illuminate rear license plate	Seal rear closure opening	Separate airflow at roof rear	Allow rear visibility	Remove dirt from DLO	Illuminate (CHMSL function)	Lock rear closure	Illuminate (Tail function)	Reflect light to the rear of the vehicle	Reflect light to the side of the vehicle	Illuminate (turn signal function)	Illuminate (side marker function)	Illuminate (stop function)	Illuminate (back up function)	Absorb impact energy in high speed impacts (crash tests)	Avoid stone pecking damage in sheet metal A-surfaces	Sense objects rearward to the vehicle	Sense objects located at the sides of the rear fascia	Sense object in the blind spot	Display brand	Guide lift gate opening	Provide structure to A/B line (top)	Absorb impact energy in low speed damageability tests	Recover vehicle mobility after tire damage	Provide structure to A/B line (bottom)	Detect radio signal	Attach rear fascia	Attach lighting elements	Attach exterior trim systems	Locate rear fascia	Locate lighting elements	Locate exterior trim systems	Provide structure to rear fascia	Provide structure to rear closure	Provide structure to lighting elements	Provide structure to exterior trim components	Attach sheet metal components (A/B line top)	Locate sheet metal components (A/B line top)	Attach sheet metal components (A/B line bottom)	Locate sheet metal components (A/B line bottom)	Attach exhaust pipes	Locate exhaust pipe trim	Sense obstacles in rear closure motion path	Provide structure to A/B line (sides)	Attach sheet metal components (A/B line, sides)	Locate sheet metal components (A/B line, sides)
			2	3	49	4	6	11	16	17	5	7	8	9	10	12	13	33	34	35	36	42	43	18	29	30	31	32	41	1	48	14	15	44	38	20	21	22	25	26	27	39	40	45	46	23	28	52	53	19	24	37	47	50	51
34	Rear closure struts	34	1	1																																																				
33	Rear closure actuator (powered opening)	33			1																																																			
29	Rear closure handle	29				1	1																																																		
20	Rear view camera	20						1																																															
30	License plate receiver	30							1																																														
15	License plate lighting	15								1																																													
31	Seal system	31									1																																												
24	Spoiler	24										1																																											
27	Rear DLO	27											1																																										
25	Wiper system	25											1	1																																								
26	Washer system	26												1																																									
9	CHMSL	9													1																																								
6	Latch system	6														1																																							
7	Tail light	7															1																																						
13	Rear Reflex	13																1																																					
14	Side Reflex	14																	1																																				
10	Turn signal light	10																		1																																			
12	Side marker light	12																			1																																		
8	Stop light	8																				1																																	
11	Back up light	11																					1																																
16	Bumper beam	39																						1								1																								
40	Stone pecking protector	40																							1																													
18	Park aid sensors (rear)	18																								1																												
19	Park aid sensors (sides)	19																									1																											
21	Blind spot monitor	21																										1																										
22	Emblems	22																											1																									
2	Rear closure hinges	2																												1																								
3	Rear header structure	3																													1														1	1									
39	Energy absorber	39																														1																						
35	Mobility recovery system	35																															1																					
5	Cab and ring frame structure	5																																1														1	1							
28	Antenna	28																																	1																			
17	Fascia brackets	17																																		1			1			1												
41	Fascia (Class A-components)	41																																		1	1		1	1		1								1	1					
42	Lighting housings	42																																						1				1										
23	Ornaments	23																																				1			1				1									
1	Rear closure	1																																				1			1		1											
32	Exhaust system	32																																																1	1					
4	Trough structures	4																																																		1		1	1
38	Trapped objects sensor	38																																																			1		
36	Recovery device	36																																																					
37	Tie down hook	37																																																					

* A 11” x 17” version of this matrix is available in the electronic copy of this thesis.

Figure 63 - Application example, Objects x Activities DMM



Rear-end System
Objects x Activities DMM

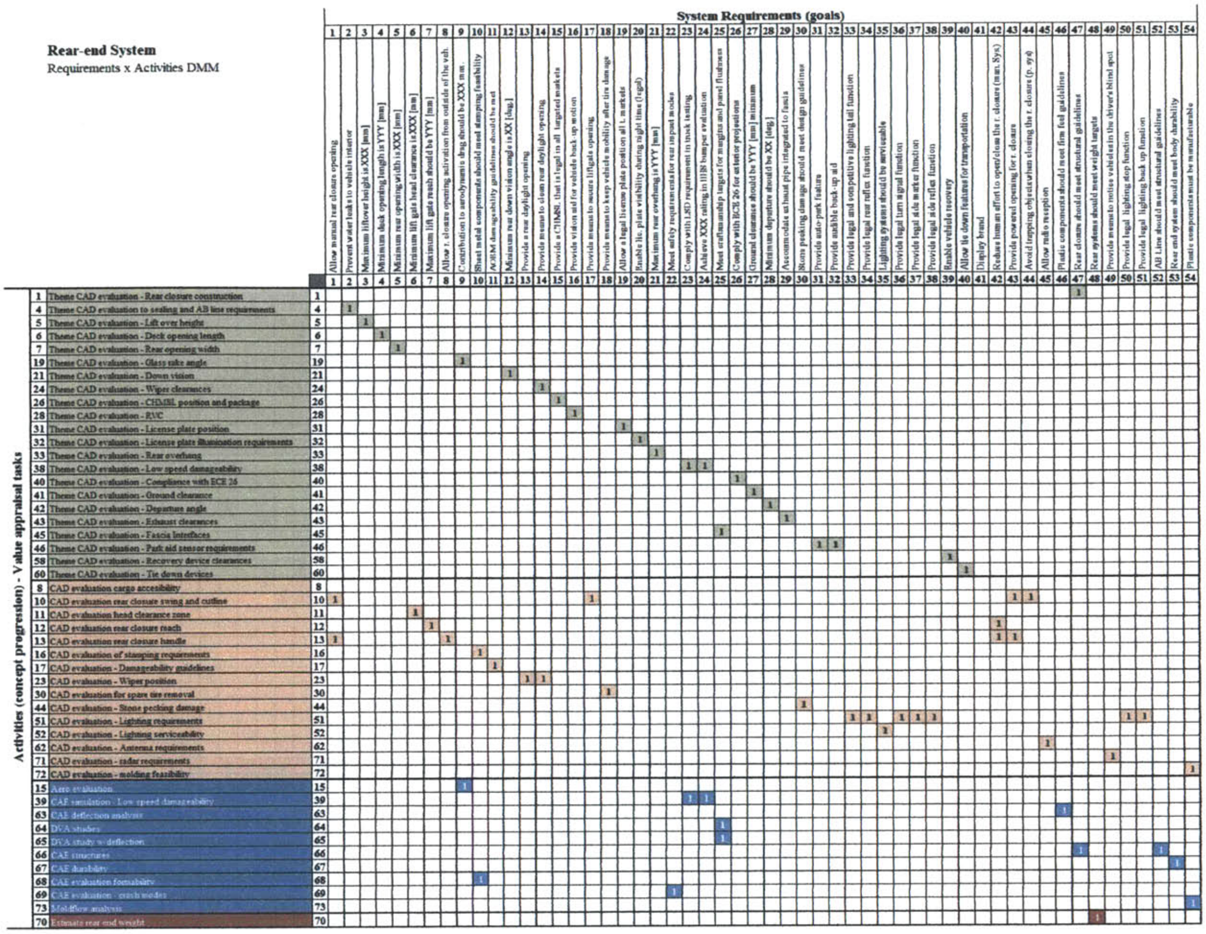
Objects (Generic system components)

Activities (Concept progression) - Data progression tasks

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
			Rear closure	Rear closure hinges	Rear header structure	Trough structures	Cab and ring frame structure	Latch system	Tail light	Stop light	CHMSL	Turn signal light	Back up light	Side marker light	Rear Reflex	Side Reflex	License plate lighting	Bumper beam	Fascia brackets and structures	Park aid sensors (rear)	Park aid sensors (sides)	Rear view camera	Blind spot monitor	Emblems	Ornaments	Spoiler	Wiper system	Washer system	Rear DLO	Antenna	Rear closure handle	License plate receiver	Seal system	Exhaust system	Rear closure actuator (powered opening)	Rear closure struts	Mobility recovery system	Recovery device	Tie down hook	Trapped objects sensor	Energy absorber	Stone pecking protector	Fascia (Class A components)	Lighting housings
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
2	CAD section through hinge	2	1	1	1																					1							1											
3	CAD section through rear closure latch	3	1				1	1										1	1												1						1				1		1	
18	CAD Section through spoiler	18	1		1						1															1			1	1			1											
20	CAD Section through backlite and rear closure	20	1														1							1	1		1	1	1		1	1												
34	CAD Section through bumper system	34	1				1	1										1	1														1	1							1		1	
35	CAD Section through beam attachment	35	1															1	1																								1	
36	CAD Section through quarter panel	36	1			1																	1										1											
37	CAD Section through bumper beam (horizontal)	37	1															1																			1						1	
49	CAD Sections - Lighting (vertical)	49	1						1	1		1	1	1	1	1																												1
50	CAD Sections - Lighting (horizontal)	50	1			1			1	1		1	1	1	1	1																												1
79	CAD Section - Trough / Rear closure	79	1			1																													1	1				1				
9	Create 3D data - Hinge	9		1																																								
14	Create 3D data - Secondary obst. Detect.	14																																						1				
22	Create ceramic paint line in rear DLO	22																											1															
25	Create 3D data - Washers	25																										1																
27	Create 3D data - CHMSL	27									1																																	
29	Create 3D data - RVC	29																				1																						
47	Create 3D data - Park aid sensors	47																		1	1																							
48	Create 3D data - Tail light	48							1																																			
53	Create 3D data - Rear Reflex	53													1																													
54	Create 3D data - Turn signal	54										1																																
55	Create 3D data - Side marker	55												1																														
56	Create 3D data - Side reflex	56														1																												
57	Create 3D data - Recovery devices and zones	57																																				1						
59	Create 3D data - Tie down devices	59																																					1					
61	Create 3D data - Emblems	61																						1																				
80	Create 3D data - Stop light	80								1																																		
81	Create 3D data - Back up light	81											1																															
82	Create 3D data - Wipers	82																									1																	
83	Create 3D data - Lighting housings	83																																										1
84	Create 3D data - Antenna	84																												1														
85	Create 3D data - BLIS	85																					1																					
86	Create 3D data - Rear handle	86																													1													
87	Create 3D data - License plate receiver	87																														1												
88	Create 3D data - Seal	88																															1											
89	Create 3D data - Exhaust system	89																																1										
90	Create 3D data - Rear closure actuator	90																																	1									
91	Create 3D data - Rear closure struts	91																																		1								
92	Create 3D data - Energy absorber	92																																							1			
93	Create 3D data - Stone pecking protector	93																																								1		
94	Create 3D data - Fascia (Class A components)	94																																									1	
95	Create 3D data - Rear closure	95	1																																									
96	Create 3D data - Rear header structure	96			1																																							
97	Create 3D data - Trough structure	97				1																																						
98	Create 3D data - Cab and ring structure	98					1																																					
99	Create 3D data - Latch and striker	99						1																																				
100	Create 3D data - License plate lamps	100															1																											
101	Create 3D data - Bumper Beam	101																1																										
102	Create 3D data - Fascia brackets and structures	102																	1																									
103	Create 3D data - Ornaments	103																							1																			
104	Create 3D data - Spoiler	104																								1																		
105	Create 3D data - Mobility recovery system	105																																			1							
106	Create 3D data - Rear DLO (Glass)	106																											1															
74	Theme data - Scan	74	1						1																	1			1			1											1	
75	Theme data - Surfaces and lines	75	1						1	1	1				1	1										1			1			1											1	
76	Theme data - Surface with interfaces	76	1						1	1	1				1	1									1	1			1	1	1	1											1	
77	Theme data - Surface with first flange	77	1						1	1	1	1	1	1	1	1								1	1	1			1	1	1	1											1	
78	Theme data - Surface with first flange, fillet and target flushness	78	1						1	1	1	1	1	1	1	1	1							1	1	1			1	1	1	1											1	

* A 11" x 17" version of this matrix is available in the electronic copy of this thesis.

Figure 64 - Application example, Requirements x Activities DMM



Rear-end System
Requirements x Activities DMM

System Requirements (goals)

Activities (concept progression) - Value appraisal tasks

			1 Allow manual rear closure opening	2 Prevent water leaks to vehicle interior	3 Maximum liftover height is XXX [mm]	4 Minimum deck opening length is YYY [mm]	5 Minimum rear opening width is XXX [mm]	6 Minimum lift gate head clearance is XXX [mm]	7 Maximum lift gate reach should be YYY [mm]	8 Allow r. closure opening activation from outside of the veh.	9 Contribution to aerodynamic drag should be XXX max.	10 Sheet metal components should meet stamping feasibility	11 AOEM damageability guidelines should be met	12 Minimum rear down vision angle is XX [deg.]	13 Provide a rear daylight opening	14 Provide means to clean rear daylight opening	15 Provide a CHMSL that is legal in all targeted markets	16 Provide vision aid for vehicle back-up motion	17 Provide means to secure liftgate opening	18 Provide means to keep vehicle mobility after tire damage	19 Allow a legal license plate position all t. markets	20 Enable lic. plate visibility during night time (legal)	21 Maximum rear overhang is YYY [mm]	22 Meet safety requirements for rear impact modes	23 Comply with LSD requirement in truck testing	24 Achieve XXX rating in IIHS bumper evaluation	25 Meet craftsmanship targets for margins and panel flushness	26 Comply with ECE 26 for exterior projections	27 Ground clearance should be YYY [mm] minimum	28 Minimum departure should be XX [deg.]	29 Accommodate exhaust pipe integrated to fascia	30 Stone pecking damage should meet design guidelines	31 Provide auto-park feature	32 Provide audible back-up aid	33 Provide legal and competitive lighting tail function	34 Provide legal rear reflex function	35 Lighting systems should be serviceable	36 Provide legal turn signal function	37 Provide legal side marker function	38 Provide legal side reflex function	39 Enable vehicle recovery	40 Allow tie down features for transportation	41 Display brand	42 Reduce human effort to open/close the r. closure (man. Sys.)	43 Provide powered opening for r. closure	44 Avoid trapping objects when closing the r. closure (p. sys)	45 Allow radio reception	46 Plastic components should meet firm feel guidelines	47 Rear closure should meet structural guidelines	48 Rear systems should meet weight targets	49 Provide means to notice vehicles in the driver's blind spot	50 Provide legal lighting stop function	51 Provide legal lighting back up function	52 AB Line should meet structural guidelines	53 Rear end system should meet body durability	54 Plastic components must be manufacturable
1	Theme CAD evaluation - Rear closure construction	1																																														1							
4	Theme CAD evaluation to sealing and AB line requirements	4		1																																																				
5	Theme CAD evaluation - Lift over height	5			1																																																		
6	Theme CAD evaluation - Deck opening length	6				1																																																	
7	Theme CAD evaluation - Rear opening width	7					1																																																
19	Theme CAD evaluation - Glass rake angle	19									1																																												
21	Theme CAD evaluation - Down vision	21												1																																									
24	Theme CAD evaluation - Wiper clearances	24														1																																							
26	Theme CAD evaluation - CHMSL position and package	26															1																																						
28	Theme CAD evaluation - RVC	28																1																																					
31	Theme CAD evaluation - License plate position	31																			1																																		
32	Theme CAD evaluation - License plate illumination requirements	32																				1																																	
33	Theme CAD evaluation - Rear overhang	33																					1																																
38	Theme CAD evaluation - Low speed damageability	38																							1	1																														
40	Theme CAD evaluation - Compliance with ECE 26	40																									1																												
41	Theme CAD evaluation - Ground clearance	41																										1																											
42	Theme CAD evaluation - Departure angle	42																											1																										
43	Theme CAD evaluation - Exhaust clearances	43																												1																									
45	Theme CAD evaluation - Fascia Interfaces	45																								1																													
46	Theme CAD evaluation - Park aid sensor requirements	46																													1	1																							
58	Theme CAD evaluation - Recovery device clearances	58																																						1															
60	Theme CAD evaluation - Tie down devices	60																																							1														
8	CAD evaluation cargo accesibility	8																																																					
10	CAD evaluation rear closure swing and cutline	10	1																1																										1	1										
11	CAD evaluation head clearance zone	11						1																																																
12	CAD evaluation rear closure reach	12							1																																			1												
13	CAD evaluation rear closure handle	13	1							1																																		1	1											
16	CAD evaluation of stamping requirements	16										1																																											
17	CAD evaluation - Damageability guidelines	17											1																																										
23	CAD evaluation - Wiper position	23													1	1																																								
30	CAD evaluation for spare tire removal	30																		1																																				
44	CAD evaluation - Stone pecking damage	44																														1																								
51	CAD evaluation - Lighting requirements	51																																	1	1		1	1	1													1	1			
52	CAD evaluation - Lighting serviceability	52																																			1																			
62	CAD evaluation - Antenna requirements	62																																													1									
71	CAD evaluation - radar requirements	71																																																	1					
72	CAD evaluation - molding feasibility	72																																																					1
15	Aero evaluation	15									1																																												
39	CAE simulation - Low speed damageability	39																							1	1																														
63	CAE deflection analysis	63																																														1								
64	DVA studies	64																								1																														
65	DVA study w deflection	65																								1																														
66	CAE structures	66																																															1					1		
67	CAE durability	67																																																					1	
68	CAE evaluation formability	68										1																																											
69	CAE evaluation - crash modes	69																						1																																
73	Moldflow analysis	73																																																					1
70	Estimate rear end weight	70																																																1						

* A 11" x 17" version of this matrix is available in the electronic copy of this thesis.

Figure 65 – Application example Objects x Requirements DMM

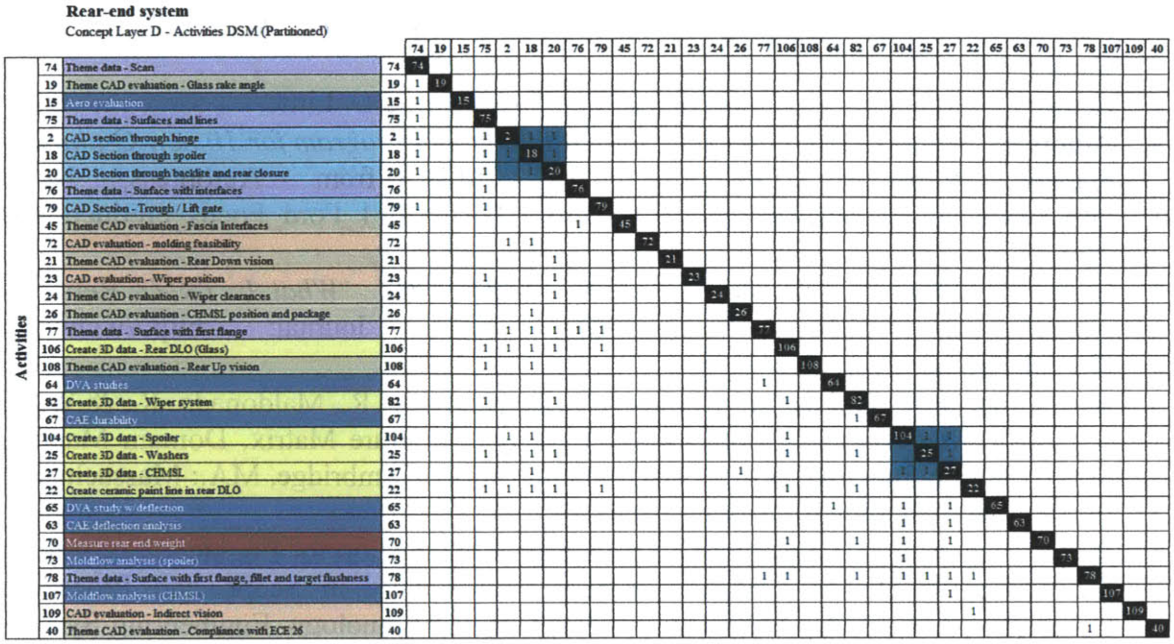
Rear-end System
Objects x Requirements DMM

			Objects (Generic system components)																																									
	System Requirements (goals)		1 Rear closure	2 Rear closure hinges	3 Rear header structure	4 Trough structures	5 Cab and ring frame structure	6 Latch system	7 Tail light	8 Stop light	9 CHMSL	10 Turn signal light	11 Back up light	12 Side marker light	13 Rear Reflex	14 Side Reflex	15 License plate lighting	16 Bumper beam	17 Fascia brackets and structures	18 Park aid sensors (rear)	19 Park aid sensors (sides)	20 Rear view camera	21 Blind spot monitor	22 Emblems	23 Ornaments	24 Spoiler	25 Wiper system	26 Washer system	27 Rear DLO	28 Antenna	29 Rear closure handle	30 License plate receiver	31 Seal system	32 Exhaust system	33 Rear closure actuator (powered opening)	34 Rear closure struts	35 Mobility recovery system	36 Recovery device	37 Tie down hook	38 Trapped objects sensor	39 Energy absorber	40 Stone pecking protector	41 Fascia (Class A components)	42 Lighting housings
1	Allow manual rear closure opening	1																													1					1								
2	Prevent water leaks to vehicle interior	2																															1											
3	Maximum liftover height is XXX [mm]	3	1				1	1											1																								1	
4	Minimum deck opening length is YYY [mm]	4			1		1																																					
5	Minimum rear opening width is XXX [mm]	5				1																																						
6	Minimum lift gate head clearance is XXX [mm]	6	1	1	1																																							
7	Maximum lift gate reach should be YYY [mm]	7	1	1	1																																							
8	Allow r. closure opening activation from outside of the veh.	8																													1													
9	Contribution to aerodynamic drag should be XXX max.	9																								1			1															
10	Sheet metal components should meet stamping feasibility	10	1		1	1	1																																					
11	AOEM damageability guidelines should be met	11	1						1										1													1					1						1	
12	Minimum rear down vision angle is XX [deg.]	12																									1		1															
13	Provide a rear daylight opening	13																									1		1															
14	Provide means to clean rear daylight opening	14																									1	1																
15	Provide a CHMSL that is legal in all targeted markets	15									1																																	
16	Provide vision aid for vehicle back-up motion	16																				1																						
17	Provide means to secure liftgate opening	17						1																																				
18	Provide means to keep vehicle mobility after tire damage	18																																			1							
19	Allow a legal license plate position all t. markets	19																														1												
20	Enable lic. plate visibility during night time (legal)	20															1																											
21	Maximum rear overhang is YYY [mm]	21																																									1	
22	Meet safety requirements for rear impact modes	22			1	1	1																																					
23	Comply with LSD requirement in truck testing	23																	1																						1		1	
24	Achieve XXX rating in IIHS bumper evaluation	24																1	1																						1		1	
25	Meet craftsmanship targets for margins and panel flushness	25	1	1				1	1	1	1	1	1		1	1	1		1	1	1	1		1	1	1		1	1	1	1		1	1									1	
26	Comply with ECE 26 for exterior projections	26	1						1	1	1	1	1		1	1	1			1	1	1		1	1	1	1	1	1	1	1		1	1									1	
27	Ground clearance should be YYY [mm] minimum	27																																1									1	
28	Minimum departure should be XX [deg.]	28																																1									1	
29	Accommodate exhaust pipe integrated to fascia	29																																1									1	
30	Stone pecking damage should meet design guidelines	30																																								1	1	
31	Provide auto-park feature	31																		1	1																						1	
32	Provide audible back-up aid	32																		1																							1	
33	Provide legal and competitive lighting tail function	33							1																																			1
34	Provide legal rear reflex function	34													1																													1
35	Lighting systems should be serviceable	35							1	1	1	1	1				1																											
36	Provide legal turn signal function	36										1																																1
37	Provide legal side marker function	37												1																														1
38	Provide legal side reflex function	38														1																												1
39	Enable vehicle recovery	39																																				1					1	
40	Allow tie down features for transportation	40																																					1				1	
41	Display brand	41																						1																				
42	Reduce human effort to open/close the r. closure (man. Sys.)	42																																		1								
43	Provide powered opening for r. closure	43																													1				1									
44	Avoid trapping objects when closing the r. closure (p. sys)	44																																						1				
45	Allow radio reception	45																												1														
46	Plastic components should meet firm feel guidelines	46																	1					1	1	1																	1	
47	Rear closure should meet structural guidelines	47	1																																									
48	Rear systems should meet weight targets	48	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
49	Provide means to notice vehicles in the driver's blind spot	49																					1																					
50	Provide legal lighting stop function	50								1																																		
51	Provide legal lighting back up function	51											1																															
52	AB Line should meet structural guidelines	52			1	1	1																																					
53	Rear end system should meet body durability	53	1	1	1	1	1	1										1									1							1	1	1			1					
54	Plastic components must be manufacturable	54							1	1	1	1	1		1	1			1	1	1			1	1	1				1	1	1												

* A 11" x 17" version of this matrix is available in the electronic copy of this thesis.

Figure 66 – Application example, Requirements x Objects DMM

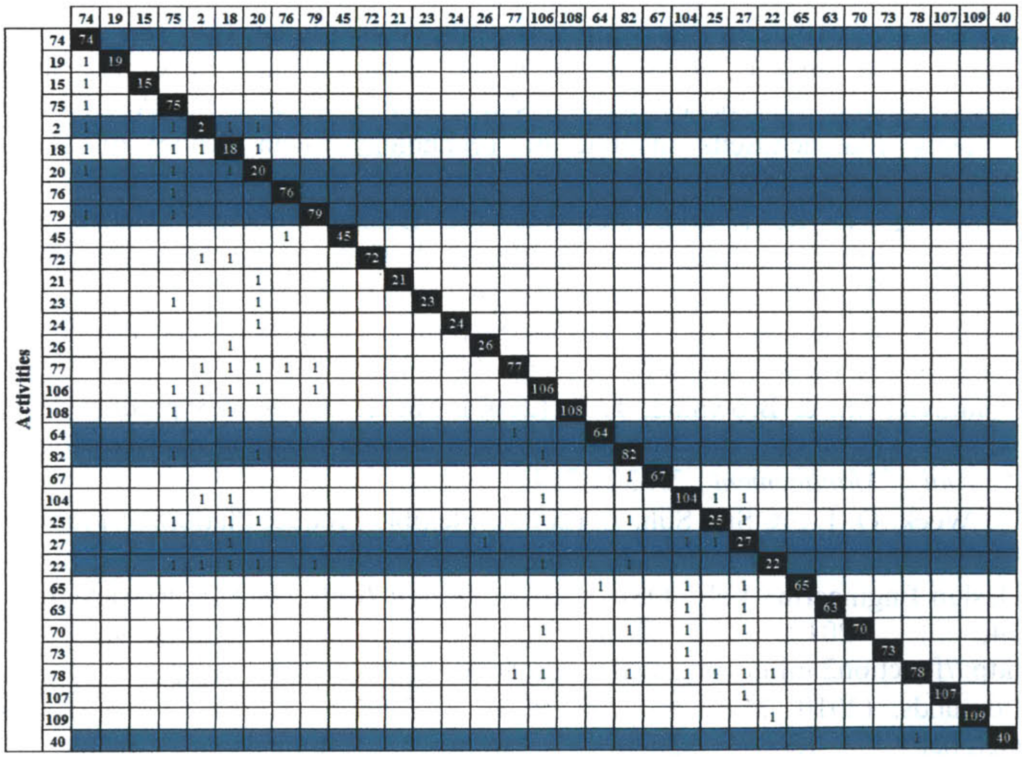
Partitioned DSM (top), banding analysis (bottom)



Rear-end system

Concept Layer D - Activities DSM (Partitioned)

				74	19	15	75	2	18	20	76	79	45	72	21	23	24	26	77	106	108	64	82	67	104	25	27	22	65	63	70	73	78	107	109	40
Activities	74	Theme data - Scan	74	74																																
	19	Theme CAD evaluation - Glass rake angle	19	1	19																															
	15	Aero evaluation	15	1		15																														
	75	Theme data - Surfaces and lines	75	1			75																													
	2	CAD section through hinge	2	1			1	2	1	1																										
	18	CAD Section through spoiler	18	1			1	1	18	1																										
	20	CAD Section through backlite and rear closure	20	1			1		1	20																										
	76	Theme data - Surface with interfaces	76				1				76																									
	79	CAD Section - Trough / Lift gate	79	1			1					79																								
	45	Theme CAD evaluation - Fascia Interfaces	45								1		45																							
	72	CAD evaluation - molding feasibility	72					1	1					72																						
	21	Theme CAD evaluation - Rear Down vision	21							1					21																					
	23	CAD evaluation - Wiper position	23				1			1						23																				
	24	Theme CAD evaluation - Wiper clearances	24							1							24																			
	26	Theme CAD evaluation - CHMSL position and package	26						1									26																		
	77	Theme data - Surface with first flange	77					1	1	1	1	1							77																	
	106	Create 3D data - Rear DLO (Glass)	106				1	1	1	1		1								106																
	108	Theme CAD evaluation - Rear Up vision	108				1		1												108															
	64	DVA studies	64																1			64														
	82	Create 3D data - Wiper system	82				1			1										1			82													
	67	CAE durability	67																				1	67												
	104	Create 3D data - Spoiler	104					1	1											1					104	1	1									
	25	Create 3D data - Washers	25				1		1	1										1			1			25	1									
	27	Create 3D data - CHMSL	27						1									1							1	1	27									
	22	Create ceramic paint line in rear DLO	22				1	1	1	1		1								1			1					22								
	65	DVA study w/deflection	65																			1			1		1		65							
	63	CAE deflection analysis	63																						1		1			63						
	70	Measure rear end weight	70																	1			1		1		1				70					
	73	Moldflow analysis (spoiler)	73																						1							73				
	78	Theme data - Surface with first flange, fillet and target flushness	78																1	1			1		1	1	1	1					78			
	107	Moldflow analysis (CHMSL)	107																								1							107		
	109	CAD evaluation - Indirect vision	109																									1							109	
	40	Theme CAD evaluation - Compliance with ECE 26	40																														1			40



		74	19	15	75	2	18	20	76	79	45	72	21	23	24	26	77	106	108	64	82	67	104	25	27	22	65	63	70	73	78	107	109	40
Activities	74	74																																
	19	1	19																															
	15	1		15																														
	75	1			75																													
	2	1			1	2	1	1																										
	18	1			1	1	18	1																										
	20	1			1		1	20																										
	76				1				76																									
	79	1			1					79																								
	45								1		45																							
	72					1	1					72																						
	21							1					21																					
	23				1			1						23																				
	24							1							24																			
	26						1									26																		
	77					1	1	1	1	1							77																	
	106				1	1	1	1		1								106																
	108				1		1												108															
	64																1			64														
	82				1			1										1			82													
	67																				1	67												
	104					1	1											1					104	1	1									
	25				1		1	1										1			1			25	1									
	27						1									1							1	1	27									
	22				1	1	1	1		1								1			1					22								
	65																			1			1		1		65							
	63																						1		1			63						
	70																	1			1		1		1				70					
	73																						1							73				
	78																1	1			1		1	1	1	1					78			
	107																								1							107		
	109																									1							109	
	40																														1			40

*** A 11" x 17" version of this matrix is available in the electronic copy of this thesis.**

Bibliography

- Allen, T. J. (1977). *Managing the Flow of Technology: Technology Transfer and the Dissemination of Technological Information within the R&D Organization.* Cambridge, MA: MIT Press.
- Arthur D. Little. (2009). *Future of Mobility 2020.* Arthur D. Little.
- Autopress News. (2010, February 5). *First of a global program for 10 new C-platform models.* Retrieved December 19, 2010, from Autopress News: http://www.autopressnews.com/2010/02/Ford_Focus/2011_Ford_Focus_production.shtml
- Barry, K., Domb, E., & Slocum, M. S. (2006). *TRIZ - What Is TRIZ?* Retrieved August 8, 2010, from The TRIZ Journal: http://www.triz-journal.com/archives/what_is_triz/
- Bartolomei, J. E., Cokus, M., Dahlgren, J., de Neufville, R., Maldonado, R., & Wilds, J. (2007). Analysis and Applications of Design Structure Matrix, Domain Mapping Matrix and Engineering System Matrix Frameworks. Cambridge, MA.: Massachusetts Institute of Technology. Working Paper.
- Bartolomei, J. (2007). Qualitative Knowledge Construction for Engineering Systems: Extending the Design Structure Matrix Methodology in Scope and Procedure. Cambridge, MA., MA.: Massachusetts Institute of Technology. Engineering Systems Division. Doctoral Dissertation.
- BBC News. (2010, January 11). *China car sales 'overtook the US' in 2009.* Retrieved October 15, 2010, from BBC: http://news.bbc.co.uk/2/hi/8451887.stm
- Black, T. A., Fine, C. H., & Sachs, E. M. (1990, October). A Method for Systems Design Using Precedence Relationships: An application to Automotive Brake Systems. Massachusetts Institute of Technology Sloan School of Management. Working Paper #3208-90-MS.
- Browning, T. R. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. *IEEE Transactions on Engineering Management, 48* (3), 292-306.
- Clark, K. B., & Fujimoto, T. (1990, November-December). The Power of Product Integrity. *Harvard Business Review* , pp. 107-118.
- Danilovic, M., & Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Management, 25*, 300-314.
- De Weck, O. L., & Suk Suh, E. (2006). Flexible Product Platforms: Framework and Case Study. *ASME IDETC/CIE* . Philadelphia, PA. USA.
- Design Engineering Lab | OSU. (2010). *Design Tools Tutorial.* Retrieved November 14, 2010, from Design Engineering Lab: http://function2.mime.oregonstate.edu:8080/view/searchmorph.jsp
- Edmunds. (2010, May 28). *VW Plans $1.2-Billion China Expansion.* Retrieved October 15, 2010, from Edmunds Inside line: http://www.insideline.com/volkswagen/vw-plans-12-billion-china-expansion.html

- Fernandez, C. I. (1998). Integration Analysis of Product Architecture to Support Effective Team Co-location. Cambridge, MA.: Massachusetts Institute of Technology. SM Thesis.
- Financial Times. (2010, August 26). *Ford targets India for assembly growth.* Retrieved October 15, 2010, from Ft.com/ Asia-Pacific / India: http://www.ft.com/cms/s/0/9a61dce6-b09a-11df-8c04-00144feabdc0,dwp_uuid=a6dfcf08-9c79-11da-8762-0000779e2340.html
- GM. (2010, July 19). *GM China Breaks Ground for Advanced Technical Center in Shanghai.* Retrieved October 15, 2010, from GM Media / China: http://media.gm.com/content/media/cn/en/news/news_detail.brand_gm.html/content/Pages/news/cn/en/2010/July/0719
- http://http-server.carleton.ca/~gkardos/88403/CREAT/MORPHO.html. (n.d.). *MORPHOLOGICAL METHOD.* Retrieved November 9, 2010, from http://http-server.carleton.ca/~gkardos/88403/CREAT/MORPHO.html: http://http-server.carleton.ca/~gkardos/88403/CREAT/MORPHO.html
- IBISWorld. (2010). *Global Automobile and Light Duty Motor Vehicle Manufacturing.* IBISWorld Inc.
- IIHS. (2010, December 22). *IIHS vehicle ratings.* Retrieved January 17, 2011, from Insurance Institute for Highway Safety: http://www.iihs.org/ratings/default.aspx
- J. D. Power. (2010). *2010 Initial Quality Study Results* . Retrieved October 15, 2010, from J.D. Power: http://www.jdpower.com/autos/articles/2010-Initial-Quality-Study-Results/
- J.D. Power and Associates. (2010). *Ratings: New & Used Cars.* Retrieved January 17, 2011, from JDPower.com: http://www.jdpower.com/autos/car-ratings
- Kalligeros, K. (2006). Platforms and Real Options in Large-Scale Engineering Systems. Cambridge, MA.: Massachusetts Institute of Technology. Engineering Systems Division. Doctoral Dissertation.
- Kroll, E., Condoor, S. S., & Jansson, D. G. (2001). *Innovative Conceptual Design.* New York: Cambridge University Press.
- Macy, S., & Wardle, G. (2008). *H-point. The fundamentals of car design and packaging.* Design Studio Press.
- March, A. (1994, August). Apple PowerBook: Design Quality and Time to Market. *Design Management Institute Case Study* . Boston: HBS publishing.
- McCord, K. R., & Eppinger, S. D. (1993). Managing the integration problem in concurrent engineering. Cambridge, MA: Massachusetts Institute of Technology Sloan School of Management. Working Paper #3594-93-MSA.
- McCormick, W. T., Schweitzer, P. J., & White, T. W. (1972). Problem Decomposition and Data Reorganization by a Clustering Technique. *INFORMS Operations Research Journal , 20* (5), 993-1009.
- Miller, G. A. (1956). The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. *Psychological Review , 63*, 81-97.
- MIT. (2008). *SDM.* Retrieved January 23, 2011, from News and articles: http://sdm.mit.edu/news/news_articles/sdm_keio/v_model.jpg
- Morgan, J. M., & Liker, J. K. (2006). *The Toyota Product Development System.* New York, NY: Productivity Press.

- Netcarshow.com. (n.d.). *Car pictures and wallpapers*. Retrieved January 9, 2010, from Netcarshow.com: http://www.netcarshow.com/
- Pimmler, T. a. (1994). Integration Analysis of Product Decompositions. *ASME Design Theory and Methodology Conference.* Minneapolis, MN.
- Pugh, S. (1981). Concept Selection - A Method that Works. *International Conference on Engineering Design. ICED 81*, (pp. 497-506). Rome, Italy.
- Reuters. (2010, March 28). *Geely signs $1.8 billion deal for Ford's Volvo car unit.* Retrieved October 15, 2010, from Reuters: http://www.reuters.com/article/idUSTRE62Q1F520100328
- Ross, A. M., & Rhodes, D. H. (2008). Using Attribute Classes to Uncover Latent Value during Conceptual Systems Design. *IEEE International Systems Conference.* Montreal, Canada: SysCon 2008.
- Simpson, T. W. (2001). Product Platform Design: Method and Application. *Research in Engineering Design*, *13* (1), 2-22.
- Society of Automotive Engineers . (2010, January 15). *SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler*. Retrieved January 16, 2011, from SAE International: http://standards.sae.org/j1772_201001
- Standard & Poor's. (2010). *Industry Surveys - Autos & Auto Parts.* New York, NY: Standard & Poor's.
- *Staple gun redesign - DDWiki.* (n.d.). Retrieved November 20, 2010, from http://ddl.me.cmu.edu/ddwiki/index.php/Staple_gun_redesign
- Steward, D. (1981). The Design Structure System: A method for managing the design of complex systems. *IEEE Transaction on Engineering Management*, *28*, 71-74.
- Tata Motors. (2008, June 2). *Tata Motors completes acquisition of Jaguar Land Rover*. Retrieved October 15, 2010, from Tata Motors - Media Centre: http://www.tatamotors.com/our_world/press_releases.php?ID=370&action=Pull
- Thebeau, R. E. (2001, February). Knowlege Management of System Interfaces and Interactions for Product Development Processes. Massachusetts Institute of Technology. SM Thesis.
- Thomke, S., & Nimgade, A. (2007, april 26). IDEO Product Development. *HBS case study* . Harvard Business School.
- Ulrich, K., & Eppinger, S. (2008). *Product Design and Development.* McGraw-Hill Higher Education.
- Ward, A., Liker, J., & Cristiano, J. (1995). The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster. *Sloan Management Review* , *Spring 1995*, pp. 43-61.
- Ward, A., Sobek, D., & Liker, J. (1999). Toyota's Principles of Set-Based Concurrent Engineering. *Sloan Management Review* , *Winter 1999*, pp. 67-83.
- Wilds, J. M. (2008, September). A Methodology for Identifying Flexible Design Opportunities. Cambridge, Massachusetts: Massachusetts Institute of Technology. Engineering Systems Division. Master's Thesis.
- Zwicky, F. (1969). *Discovery, Invention, Research-through the Morphological Approach.* Toronto: The Macmillian Company.