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Optimizing The Level Of Customization For Products In Mass Customization Systems

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OPTIMIZING THE LEVEL OF CUSTOMIZATION FOR PRODUCTS IN MASS CUSTOMIZATION SYSTEMS

by

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ABSTRACT

Mass customization (MC) was developed to capitalize on the combined benefits of economies of scale and economies of scope. Balancing the tradeoffs involved in an MC system warrants the determination of the degree or the extent of customization. Most of the literature views the degree of customization as how early or how far the customer is integrated in the production cycle, which is defined as the order decoupling point. In this study we are addressing the degree of customization from a product structural perspective.

There are two objectives in this research. The first is to develop a unit of measurement for the degree of customization of a product in an MC system. The second is to construct an optimization model to determine the level of customization that would best satisfy the organizational goals.

The term "Magnitude of Customization" (MOC) has been introduced as a measuring unit for the degree of customization on a customization scale (CS). The MOC is based on the number of module options or the extent of customizable features per component in a product.

To satisfy the second objective, an analytical model based on preemptive goal programming was developed. The model optimizes the solution as to how far an organization should customize a product to best satisfy its strategic goals. The model considers goals such as increasing the market share, and attaining a higher level of customer satisfaction, while keeping the risk or budget below a certain amount. A step-by-step algorithm is developed for the model application.

A case study of an aluminum windows and doors company is used to verify and validate the model. A double panel sliding window is selected as the subject of our study. Information related to company goals and objectives vis-à-vis customization is gathered, through interviews and questionnaires, from the upper management including Operations, Marketing, and Finance Departments. The Window design and technical information are collected from the Manufacturing Department.

The model and its solution provided specific recommendations on what to customize and to what degree to best satisfy primary strategic goals for the organization. Results from the model application shows that the company is able to meet the five goals that they had identified with two goals having a deviation of 4.7% and 6.6% from the targets. To achieve the stated goals, the model recommends an overall degree of customization of approximately 32.23% and delineates that to the component and feature levels. For validation, the model results are compared to the actual status of the company and the manufacturer's recommendation without prior information about the model outcome. The average difference, for attaining the same goals, is found to be 6.05%, at a standard deviation of 6.02% and variance of 36.29%, which is considered adequately close.

The proposed model presents a framework that combines various research efforts into a flexible but encompassing method that can provide decision-makers with essential production planning guidelines in an MC setup. Finally, suggestions are provided as to how the model can be expanded and refined to include goal formulations that accommodate potential MC systems and technology advances.

To the best of our knowledge, this research is a pioneer in quantifying customization in an MC environment and relating it to the organizational goals through modeling and optimization.

To my parents, whom without their love, undeterred encouragement and belief in me, I

would never be where I am.

ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

AHP: Analytical Hierarchy Process

AM: Agile Manufacturing / Additive Manufacturing

BTO: Built To Order

CAD: Computer Aided Design

CBP: Component Based Product

CC: Customer Closeness

CDFMC: Concurrent Design for Mass Customization

CE: Concurrent Engineering

CNC: Computer Numerical Control

CI: Consistency Index

CRM: Customer Relationship Management

CS: Customization Scale

DFMA: Design for Manufacturability and Assembly

DFMC: Design for Mass Customization

DFX: Design for X

DMD: Direct Metal deposition

DPD: Delayed Product Differentiation

DOC: Discrete Option Components

FBD: Family Based Design

FBC:	Feature Based Component
FBP:	Feature Based Product
FGI:	Finished Goods inventory
FMS:	Flexible Manufacturing Systems
GMOC:	Global Magnitude of Customization
GP:	Goal Programming
IFMC:	Infrastructure for Mass customization
IT:	Information Technology
LasForm:	Laser Forming
LENS:	Laser Energizes Net Shaping
MBMP:	Modular-Based Manufacturing Practices
MCM:	Mass Customization manufacturing
MC:	Mass Customization
MFD:	Modular function Deployment
MIM:	Module Identification Matrix
MIS	Management Information Systems
MOC:	Magnitude of Customization
PFA:	Product Family Architecture
PFD:	Product Family Design
QFD:	Quality Function Deployment
RM:	Rapid Manufacturing
RP:	Rapid Prototyping
RT:	Rapid Tooling

SFF: Solid Freeform Fabrication

TQM: Total Quality Management

CHAPTER 1: INTRODUCTION

1.1   Background on Mass Customization

We are living in a dynamic world of continuous improvement and progress. Whenever it seems that optimality for the current manufacturing systems has been achieved, new concepts emerge shifting the industry into a higher level of efficiency. The evolution of production and manufacturing systems occurred at several stages. Starting at a one-to-one customization, Craft Production was operating at a low volume of production, satisfying each customer one at a time. It was not until the modern industrial revolution that ideology of standardization and economies of scale were conceived. The advanced machinery, tools and production systems enabled the development of mass production. However, the ongoing competition lead manufacturers to improve the efficiency and reliability of their existing processes, by implementing new quality initiatives, such as Total Quality Management (TQM) and Design for Six Sigma; and minimizing waste by applying Lean principles. While the existing systems are being persistently upgraded to better serve the customer, the current and diversified market is becoming even harder to satisfy. Agile Manufacturing has been developed to mitigate the effects of the ongoing and ever increasing turbulence in customer satisfaction. That was achieved by helping the industry better reconfigure or form virtual enterprises to better respond to changes in demand.

There was a call for new concept that thrives upon, rather than deals with, diversification and personalization. The "one size fit" model is out-of-date; it does not represent the dominant

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part of the market anymore. People are now more informed, able and wiling to make their own decisions; they want to be treated as individuals, and are prepared to pay an extra price for that. Mass customization (MC) by targeting economies of scope captures the extra benefits of customization while keeping most of economies of scale's efficiencies. MC initiatives have been developed to introduce the concept to companies that were traditionally operating mostly on mass production; or to provide the appropriate Infrastructure for Mass Customization (IFMC) for newly emerging companies or systems.

Design for Mass Customization (DFMC) deals with MC from a product development viewpoint, which aims at extending the boundaries of product design to encompass a larger scope of planning for sales and marketing. It also integrates Design for Manufacturability and Assembly (DFMA) with (DFMC) in concurrency at a product development stage. In DFMC the focus is on designing the best product family from a Product Family Architecture (PFA) standpoint rather than the best standard or single-fit product. It is possible to achieve that through Modular Function Deployment (MFD), which is implemented as an extension to Quality Function Deployment (QFD). MFD techniques help design modules that will form a family of products rather than an integral design for a single ideal product. Selecting the proper modules is the foundation for an MC system, because it enables to capture the communalities, while generating diversified variants. The modular architecture can be performed by starting with the end product and then decomposition it into its basic elements (functional or structural elements) and then re-composing those elements into a set of modules or individual components. Having different interchangeable versions for the same module facilitates the generation of variants, which is a main step in achieving an MC system.

In this research the focus will be more on Modularity which is the "the degree to which a system's components can be separated and recombined" (Schilling, 2000). There are several criteria that shall be analyzed to determine the tradeoff associated with customizing a mass production system. The tradeoff is between benefits and costs of increasing the product variety at the component level and personalization of products or services. The main benefits or value-added can be quantified in terms of the extra price the consumer is willing to pay for a personalized product and the additional market niches that can be captured that a standard product would not have targeted. The cost of deviation from a mass production system or providing the infrastructure for an MC system can be quantified by analyzing the following criteria: increase in component inventory level, inconveniences in procurement, cycle time challenges, variety induced complexity, upgrading information system, staff training, and use of Customer Relationship Management (CRM) systems. All those criteria are a function of modularity or the "granularity of the modules" (Duray *et al.*, 2000), which are the building blocks of an MC system. One of the aims of this research is to determine a reliable scale that will capture such tradeoffs and generate a reasonable starting point as to how far a particular company should venture in its product customization to best meet their organizational strategic goals. The characteristics of the scale may differ from one industry to another or a category of products to another based on the nature of the industry or structure of products involved.

1.2   Evolution From Mass Production to Mass Customization

Mass Production emerged during the modern industrial revolution in the early 1900s. It became a paradigm that lasted for more than half a century. "It was the King of the competitive world" (Oleson, 1998). It governed the manufacturing enterprise and "became deeply ingrained"

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(Oleson, 1998). During the world wars, most of the industries, especially the heavy industry thrived based on the concepts of mass production and standardization. Mass production became the method that resulted in the highest productivity in the industrial world. Customers, who struggled for basic needs, could not afford to be selective; survival was their priority. In this time, manufacturers based their industrial strategies, factory layout designs and sales plans on the pure principles of standardization and division of labor. Economy of Scale proved to be successful during the World War era; that is as long as there was a demand on the millions of identical commodities that were produced everyday. However, during post-war era, the market behavior started to change. New concepts emerged in light of changing market demands. Customers started to become more particular about their demands. A change in fashion could have left whole industries bankrupt. That is because it was simply too costly for some industries, that were mass oriented and highly standardized, to reconfigure their production systems in such a way to respond to a general change in demand. In order to meet such demand fluctuations some factories or companies had to be liquidated and replaced by new ones. Japan, on the other hand, did not show a complete reliance on mass production as it struggled to establish itself throughout the world. Where low volume of production was concerned, ingredients for mass production were missing, and hence a different approach was needed. This approach included the customization of products, where client's individualized needs were satisfied. If economies of scale could not be fully applied at least there would be another competitive edge. This approach has, in time, evolved to be implemented in a low to medium volume of production environment. That was where the new manufacturing paradigm of mass customization came in place. This concept aims at satisfying individuals needs while keeping most of the mass production efficiencies (Tseng and Jiao, 1998).

This new concept defies the old notions that tailor made commodities are luxury products for only the ones who can afford it. Now it is customization for the masses which is sometimes referred to as the One to One Production. However, all that is theoretically speaking. In reality, when we depart from standardization, there is often a quantifiable loss in efficiencies of pure mass production. Therefore, there is a tradeoff between this relative loss in efficiencies and the product value-added due to incorporating the element of customization. That is what makes the implementation of such a concept worth while (Tseng and Jiao, 1996; Corbett, 2005).

1.3 The Fundamental Aspects of Mass Customization

There are companies that were traditionally operating on mass production and, after realizing that venturing into MC would give them an additional competitive edge, they started applying the concept. The transformation from a mass production ideology to MC is not a simple task. It requires a culture change throughout the whole company stating from the top management to the operators. It also requires a complete process restructuring plan within the company; and a total reform throughout the supply chain from procurement to individual delivery plans. In addition, it is imperative to develop a new understanding of the customer's individualized requirements versus the traditional general market demand. Other companies prefer to start new businesses with their foundations already set in the direction of MC. Design for mass customization DFMC helps the producer establish the foundations for an MC system starting from product development to process design, all the way customer education. The following are fundamental aspects that should be considered to sustain a successful MC system:

- The scope or product differentiation that can be potentially generated as a result of implementing an MC system and the extent to which it covers the existing market niches (Piller, 2006).

- The system needs to be cost efficient. That could be achieved by making use of the communalities involved or the standardized portion of the product or service. (Piller, 2006; Tu *et al.*, 2001)

- Lead time to delivery or the response time, which is the time it takes from the customer's order to delivery (Tu *et al.*, 2001).

- The interface between the customers' personalized requirements and the production or service offered. That is the ability of the system to help the customer determine his/her need and then translating it into an accurate processing order that will fulfill the customer's exact desire (Piller, 2006).

- The volume of production should be reasonably high to capture a wide portion of the market demand (Tu *et al.*, 2001).

1.4   The Degree of Customization

Most of the literature views the degree of customization as how early or how far the customer is integrated into the production cycle. The stage at which the customer involvement or input starts in the production cycle is referred to as the Order Decoupling Point (Piller, 2006). The earlier the customer's involvement in the production cycle the higher is the degree of customization. On the other hand, the closer the customer's involvement into the final product stages and distribution, the lower is the degree of customization. In such a system, we have a combined push/pull effect, where the push portion takes place before the order decoupling point

and the pull portion follows it (Figure 1.1), where more pull indicates higher level of customization. The degree of customization can be also viewed from a supply chain perspective. A higher degree of customization would entail direct customer involvement starting backwards at the first tier suppliers, while a lower degree of customization occurs when customer involvement is close to the retailers or end users. The stage at which the customers' actual input integrates into the system is referred to as the "Stockholding Decoupling Point" (Hoekstra e*t al.*, 1992; Barlow *et al.*, 2003).
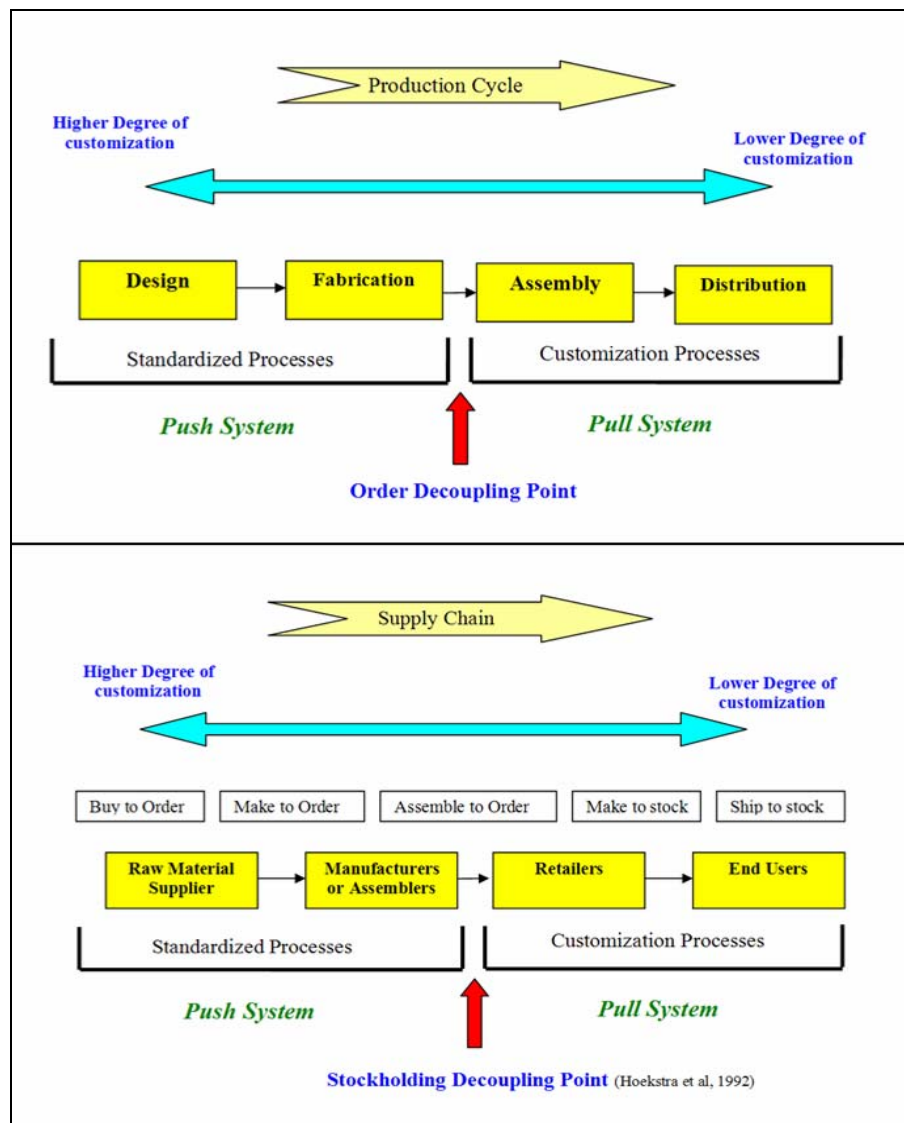
Figure 1.1 The degree of customization from a customer involvement viewpoint.

This research addresses the level of customization from a product structural design perspective. That is, the degree of customization is determined by breaking down a product into a number of modules or components, and then examining the various options for each module or the extent to which some features within each module can be changed upon demand. We also consider features that are continuously altered or have a freeform.

1.5   Research Objectives and Outline of the Dissertation

The idea behind this research is motivated by the fact that MC is becoming at this time more popular by the day. As technology is advancing new opportunities to customize cheaply and effectively are growing. More companies in the same industry are willing to follow their competitors' example and venture into MC. A clear example for that is Nike-ID™, MI-Adidas™, Puma™ and Reebok™; they all eventually ended up introducing MC. Now the competition is able to achieve has a higher degree of customization than the rest.

A need has been identified for a means of computing the degree of customization using scientific tools. This need warrants a new convention or language that will eventually improve communication between management and/or investors. The first elements of this convention are units of measurement or quantification for the degree of customization. Once such foundations are developed, they can pave the way for handling the concept of customization in a more elaborate and scientific manner. One of the ways to utilize this convention is to help answer a frequently asked question by the management or stockholders before venturing in MC: "How far or how much to customize?" Before answering this question we need to settle on what is "how much" relative to another similar "how much". The Upper management will be expecting a

different answer than the Technical or Operations Department. The former would need a general figure that will help categorize the standing of the company versus other competitors in the market. The latter would require more specific directions of the degree of customization for each customizable components or feature per product.

There are two objectives in this research. The first is to quantify the degree of customization for a product in an MC system using units of measurement. The second is to construct a model that uses the units developed in the first objective to determine the level of customization that would best satisfy the organizational goals and constraints.

Chapter 2 includes an encompassing literature review on MC. We address definitions of MC, types of customization, the foundations, structure and capabilities of an MC system. We also show how the literature views MC in relation to other paradigms such as Economies of scale, Agile Manufacturing, Concurrent Engineer, Economies of Integration and the Long Tail. Many technologies have had a major impact on the applicability of MC which is referred to as enabling technologies. In the literature review, we cover some of those technologies such as Rapid Manufacturing and Information Technology. The success of MC is founded on the application of various concepts including modularity and product variety management concepts such as Delayed Product Differentiation (DPD). The research is then narrowed to focus on the sources that address the degree of customization. Most of the sources refer to the degree of customization as the degree of customer integration to the design and production process. In this study, we address the degree of customization from a product structural perspective.

Chapter 3 covers the methodology by which the two objectives of this research shall be met. This chapter is divided into three parts. The first part discusses the theory behind the MC tradeoffs and introduces a customization scale (CS). The second part shows an approach to

quantify the degree of customization. It involves categorizing products into Component Based Products (CBP) and Feature Based Products (FBP). We also distinguish between three types of components: Standard Components, Discrete Option Components (DOC) and Feature Based Components (FBC). During this process we are coining the term Magnitude of Customization (MOC), which is a unit that expresses the extent of customization per component or feature/s of a component for a product. In the third part, we introduce a multi-criteria analytical model that utilizes techniques developed in the second part to optimize the degree of customization in such a way to best meet the company's strategic goals and objectives. This process applies preemptive goal programming as a tool to optimize the degree of customization using the MOC values as decision variable. Since an important prerequisite to the model application is the prioritization of goals, several ranking techniques have been considered and compared to find which would be most suitable for the application. In Section 3.4.3, a proposed algorithm is presented showing all the steps for application. The last section discusses how the outcome of the model can be interpreted into meaningful and useful results.

In Chapter 4, we present a case study that is used to apply, verify and validate the techniques discussed in the methodology. The candidate for the study is an aluminum windows and doors company. In collaboration with the manufacturer, information has been gathered, through interviews and questionnaires, from the upper management including the Marketing and Finance Department. The information includes the company's main organizational goals and data regarding the customer preferences towards the customization of specific features and components. In addition, technical data about the product structure have been provided by the Operations Department. In this case study, we implement the model step by step following the model algorithm that was developed in Chapter 3. The results are translated into meaningful

recommendations for the manufacture as to how far to customize each component and feature considered. It also provides the upper management with a useful tool for decision-making and benchmarking. The last section deals with evaluation of the model including verification and validation. The verification shows that the model solutions make sense and reflect the orientation of the inputs. The validation is performed by comparing the outcome of the model with the current or recommended customization level the company settled upon throughout the years. It must be noted that the management did not have prior knowledge of the model results.

In Chapter 5, the model is discussed and further research areas are identified. This includes means of improving the goals formulations and better estimating the MOC contributors. In addition, a model that considered multiple products has been suggested. The purpose of this dissertation is to introduce a quantification technique for the degree of customization in MC systems; then to demonstrate its usefulness in applications such as in optimizing customization on a component-level and feature-level to serve production planning and offer the management with new decision-making tools.

CHAPTER 2: LITERATURE REVIEW

2.1 <u>Introduction</u>

In this chapter, we analyze information related to the concept of Mass Customization (MC) and the history of how it evolved from the traditional concepts of mass production. We also review other production systems such as flexible manufacturing systems FMS, agile manufacturing and their role to MC. Technological advances, such as the internet capabilities, the new information technology (IT) tools, Rapid manufacturing, and others facilitated the implementation of MC system.

The establishment of an MC system starts from the product and process development phase. In this literature the use of MFD shall be covered in addition to several exiting methodologies on the selection of the proper modules. Some of those methodologies include mathematical formulations to better analyze the modularization aspects from various perspectives such as the number of components and interface constraints. Also heuristics have been developed to improve the module selection especially in highly complex systems. Finally, MC shall be viewed from a customer perspective, to understand how an MC system can deliver the ultimate customer value in a cost efficient manner. The aim of this literature is to research the proper background to develop a reliable quantification unit or measurement for the degree of customization in an MC system. On the other hand, the literature also covers MC from a market standpoint to be able to determine how far the MC system is achieving its target. That will pave

the way to formulate a description of the tradeoff between the extra production costs for implementing an MC system versus the additional benefits earned in the market.

2.2 Mass Customization

Mass Customization (MC) is the customization and personalization of products and services for individual customers at a near to mass production price. The concept was first conceived by Davis in *Future Perfect* (1987). It was then further developed by Pine (1993) in his book *Mass Customization - The New Frontier in Business Competition*. Pine defines Mass Customization as "the low-cost, high-quality, large-volume delivery of individually customized products" (Pine, 1993). It can be also described as "enabling a customer to decide the exact specification of a product or service, and have that product or service supplied to them at a price close to that for an ordinary mass produced alternative" (Anderson and Pine, 1997). MC is also sometimes referred to as the "One-to-One Production". This indicates that in a production line each unique product is destined to a particular customer, on a one to one basis. Piller (2006): We define mass customization as providing products and services which meet the needs of each individual customer with regard to certain product features with near mass production efficiency.

2.2.1 The Four Approaches to Mass Customization

There are four approaches to Mass Customization as was first described b y Pine and Gilmore (1997) which revolutionized the understanding of customization in an MC system.

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2.2.1.1   <u>Collaborative Customization</u>

"Collaborative customizers conduct a dialogue with individual customers to help them articulate their needs to identify the precise offering that fulfills those needs, and to make customized products for them" (Pine and Gilmore, 1997). This approach means that the customer is involved in deciding the exact features and specifications of the desired product. Naturally this leads to a relationship between the vendor and the customer that is different from the mass production scenario, where the vendor offers a product on a 'take it or leave it' basis. Mass customization takes place when a product is designed to meet the needs of an individual customer. In this research we will be mainly focusing on the collaborative approach.

Nike lately incorporated an MC production line particularly in footwear and watches. The website was launched as NikeID^{TM}, which is specialized for customers to customize their own Nike sports products online. As an example, men's sports shoes were offered by nine different models that are customizable through various different components of the shoe by a set of color option. The corresponding variations for each item are represented in Table 1. In addition, the buyers can also print their own names or special phrase on the product.
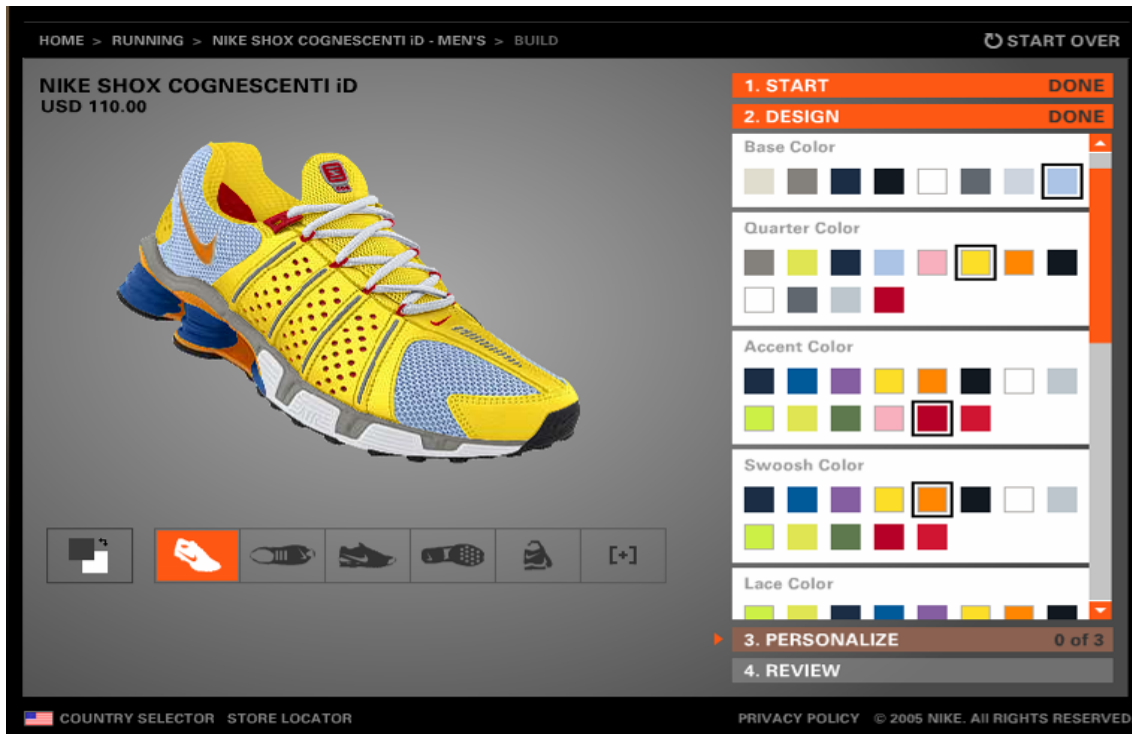
Figure 2.1 Multiple color selection
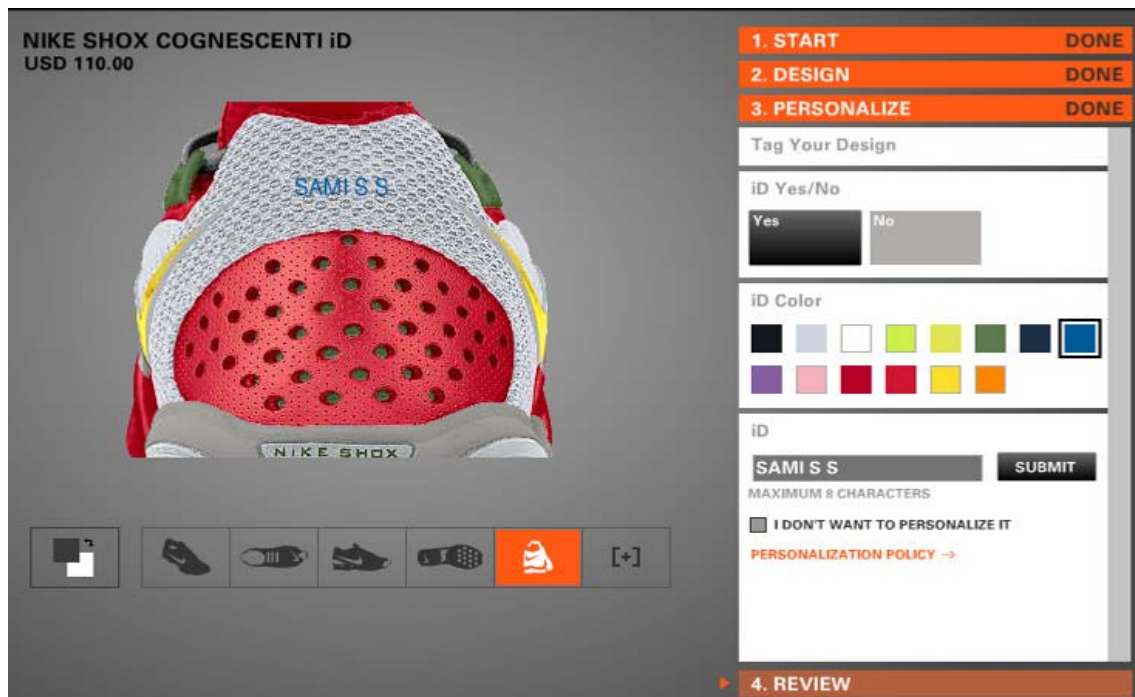
Figure 2.2 Word printing

Table 2.1 Variations for each item of a Nike Men Spots Shoe.

Aspect	Variation
Number of different models for men only	9
Number of Base colors for each model	8
Number of Quarter colors for each model	13
Number of Accent colors for each model	13
Number of Swoosh colors for each model	13
Number of Lace colors for each model	14
Number of Midsole colors for each model	4
Number of Plate colors for each model	5
Number of Shox colors for each model	9
Number of ID colors for each model	9

Each (male) customer can design online his own preferred combination of colors based on personal taste. After the order has been placed online, it only takes a few weeks to deliver. The number of possible permutations for this particular category of footwear is around 5,580,731,520! (NikeID, 2006).

2.2.1.2   Adaptive Customization

"Adaptive customizers offer one standard, but customizable, product that is designed so that users can alter it themselves." (Pine and Gilmore, 1997). A simple example for that would be the production of seats for an office environment with adaptable back inclination and height of seat. That is a common attribute that is noticed in various products around us. It offers a practical solution to the diversified demand for a single product, and saves the producer the effort of manufacturing several categories for a single product.

2.2.1.3   Cosmetic Customization

"Cosmetic Customizers present a standard product differently to different consumers" (Pine and Gilmore, 1997). An example for that is cell phone covers. Such cell phones can have a standard hardware and software structure but with modular covers that have custom colors and appearance.

2.2.1.4   Transparent Customization

"Transparent customizers provide individual customers with unique goods and services without letting them know explicitly that those products and services have been customized for them" (Pine and Gilmore, 1997). Customers sometimes have difficulty deciding what best fits them, yet they do not want to be restricted to a limited number of options where neither perfectly fits. Other customers know their needs, but do not want to state it repeatedly. In that case the producer should have the ability to define, predict, or deduce the customer's needs. The producer mainly acquires the information from market analysis, experience, and customer feedback.

Adidas introduced a new MC line that has a higher degree of customization and value than NikeID™. It does not only offer a variety of colors as is the case with Nike, but also provides a customized fitting service. This footwear line is known as Mi-Adidas™ and it helps customers design and customizes their own shoes in three simple steps:

The first step is to measure the length and width of the feet. Since a person's right and left foot are never identical, shoes can be customized to fit each individual foot based on the overall shape of the foot.
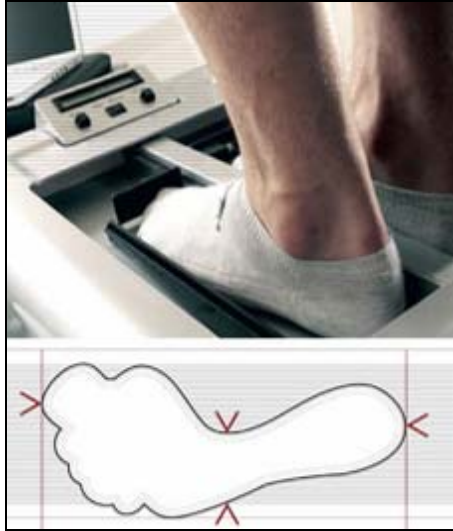
Figure 2.3 First Step: foot measurement

The second step is to take a foot scan to examine how each foot distributes pressure while in motion. That will help determine the most appropriate material and feature that best fits each unique foot.
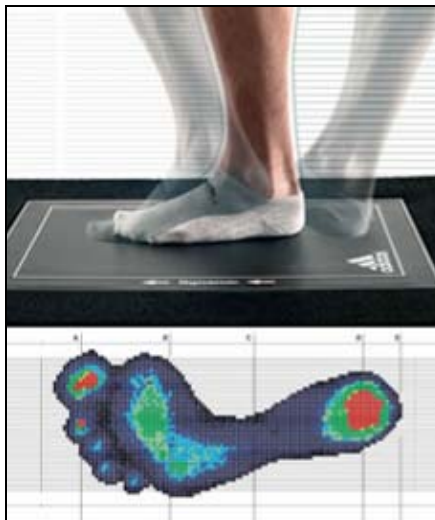
Figure 2.4 Second Step: mapping the foot pressure distribution

The third step is the cosmetic or aesthetic one, where the client gets to choose his/her colors preferences for various different parts of the sports shoes. Even the customers' personal phrase or name can be typed on printed the shoes.

Figure 2.5 Third Step: designing the shoe coloring

The challenging part is not only the high degree of customization involved in the Adidas MC system but it is also the fast response or lead time to deliver. It takes the manufacturer only 21 days to deliver the customized sport shoes given all the various features involved. It is noted that Adidas in that case implement two faces of customization: Transparent and Collaborative customization. The Transparent Customization involved the manufacturer measuring and analyzing the customer's physical attributes and using their expertise to determine for the client's the best fitting sport shoes from an ergonomic and medical standpoint, without the customer having to decide. On the other hand, during the third step the client was involved in the design of the sport shoes coloring, which represents Collaborative Customization.

It is clear that both companies operate at different degrees of customization for the same category of products. We do not claim that any of these two customization levels is superior to the other. It is just possible that each of the companies chose to operate at a customization level that better serves their organizational strategic goals and maximizes their profits. That is one of the questions this research is trying to answer.

2.2.2 The Three Pillars of Mass Customization

According to Piller (2006), to achieve a working MC environment there are three pillars or basic elements that need to be present: First, the *differentiation level,* where a considerable number of customized products and services can be generated to satisfy the unique demands of the customer. Second, is the *cost level,* where the processes and product components need to be partially standardized to capture economies of scale. Third, the *co-creation level* where customer is integrated into the design of his/her unique demand. Within those three elements lies the solution space in which an MC environment can be established.
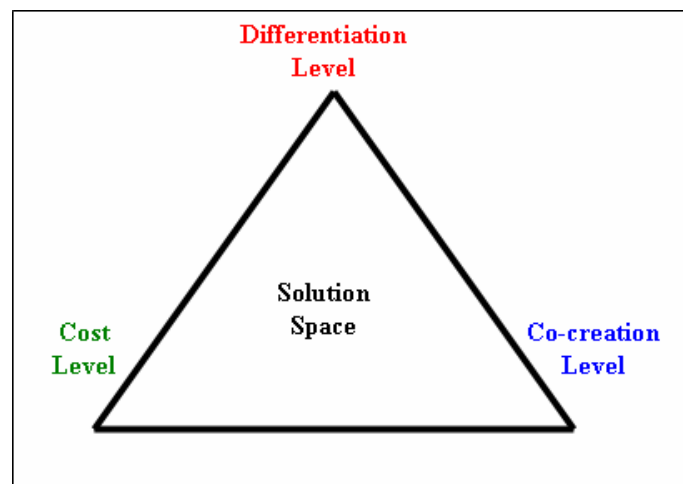
Figure 2.6 Basis of Mass Customization.

An addition aspect was also found to be important for the success of an MC system, which is the lead-time to delivery or response time (Tu *et al*., 2005). Long delivery times will slow down the capital regeneration cycle and can cause customer impatience.

2.3 The Structure of Mass Customization

Anderson and Pine (1997) explain that MC is based on the ideology of producing a family of standard set of building blocks, and a standard set of common linkages. Those building blocks sometimes referred to as "common denominators" can be assembled into a wide range of different combination. Each particular combination is based on a unique individual customer request or order. The authors describe the concept using the example of a factory for various electronic systems including "audiovisuals, communication devices, computers, electronic games, small appliances and so on". The example has been based on small instruments that can be customized with different software, circuit boards, meters, cases, dials, and various internal parts, which are considered the common denominators. The only programmable machine tools were the CNC machine and the circuit board assembly equipment. The main building block of the product in that case was the circuit board, which had bar-code identification. This bar-code is unique to every product, depending on the specifications in the customer's order. This basic part or main building block gathers more and more components as it travels along the production line. At each station there is a bar-cod reader that is capable of identifying the requirements of the product. Based on unique product information, it is decided at each work station the category of components that will be added to the product if applicable at all. For example, a product might stop at a particular work station that installs resistors of different resistances. In which case the bar code of the product will be read; that will in turn refer to a product that needs a resistor of

10Ω,. Based on that information the proper resistor will be provided. In some other case where no resistor is required, a zero Ω resistor is sometimes installed just to fill up the gap (Anderson and Pine, 1997).

In MC, also sometimes referred to as One to One production, the output products can be broken down into a set of building blocks. Those building blocks can sometimes be divided into smaller parts. However, at the bottom line there will always be a set of standard elements that can be integrated in different arrangement thus giving unique products. The presence of those standard elements enables the implementation of MC. We shall research the effect of using the technological advances in the manipulation of those building blocks, on various industries.

To achieve an effective MC system there are some general and widely known MC principles that can be applied such:

- Modularization of products, process, and teams.

- Applying the principles of postponement of customization to the retail point

- Applying DPD (Delayed Product Differentiation) where the processes that involve the customization or variation part of the product are deferred latter to the standard processes.

- Applying the principles of flexibility manufacturing, and lead time reduction.

- Extending cost effective principles throughout the supply chain in such a way to account for the customization initiatives.

- Applying DFMC principle in the product development phase.

- Customer Integration (CRM) and Market Study.

- Establishing sophisticated Information Systems.

Qiao *et al*. (2003) identified a different form of product that is being developed by Mass

Customization Manufacturing (MCM) which is referred to as "Parameterized products", those

are different than the traditional "Standardized products" and "Configured products".

Standardized products have mostly standard components, geometries, functions and

manufacturing processes. The aim is gain a competitive edge by minimizing manufacturing costs

lowing varieties; hoping to capture the largest part of a market using standard products.

Configured products are a set of predefined number of option that the customers can

chose from. Typically those variants can be realized by the configuration or mixing and

matching of various standard modules. The manufacturing costs might be slightly higher than the

case of standardized products. However, the aim is to gain a competitive edge to capture a wider

range of market niches.

Parameterized products are products that constitute a set of parameters. The idea is to

allow customers to collaborate in the design of the product during the manufacturing stage by

controlling the product "parameters" such as the sizes, shapes, features, and functions to their

desire. The manufacturing costs may exceed that of "configured products". However, the aim is

to offer a personalization service to the individual customer whom will be willing to pay a

premium price for that; in addition to capturing a much wider range of market niches. By

applying principles of MCM the manufacturing cost can still be kept at reasonable levels, which

renders feasibility to the individualization service.

2.4   The Capability of Mass Customization

The capability of MC, which can also be defined as the effectiveness of MC, addresses

how well MC is implemented. For example a bicycle manufacture may chose to apply MC

initiatives to have a competitive edge over other standard bicycle manufactures. If the tentative fails, it does not necessarily mean that venturing in MC was a poor decision. The problem might reside in the inefficient implementation of the MC principles or to make maximum use of the available technological advances. Some examples of that may be the inappropriate introduction of modularity into the system, an ineffective interface or CRM (Customer Relationship Management) system for the clients, or lack of proper use of an information technology system. Other principles such as DPD (Delayed Product Differentiation) or process postponement if applied may dramatically reduce the production costs in an MC System.

A direct measure of MC capability has been developed by Tu *et al*. (2001) including three basic components:

1) *Customization Cost Effectiveness*; which is the capability of offering a personalized product to individual customers at no or minimal extra cost to the traditional standardized products or services.

2) *Customization Volume Effectiveness*; which is the capability of availing a high product or service variety without trading it off by lowering production volume.

3) *Customization Responsiveness*: Minimizing the lead time for delivery by quickly configuring the manufacturing processes in response to individual customer requirements.

A fourth component that needs to be considered, which the author did not really address, is the "customer interface", or the means of translating the customer's desire into an individualized processing order. This interface reduces and effort it takes the customer to select design or determine the product or service that is most fitting his/her needs. Suitable CRM systems that can be accessed via the web are typically needed for that.

With the emergence of technological advances such as sophisticated and automated machinery, efficient information systems, rapid manufacturing and others, the concept of MC started to become more capable and feasible. "Mass customization capability is the ability of the firm to achieve more variety, high volume, low cost and fast deliver simultaneously through the use of advances information technology and innovative organizational practices" (Da Silveira *et al.*, 2001). Tu *et al.* (2001) came up with nine different measures as show in table 2.2.

Table 2.2 Nine items to measure the capability of MC (Tu *et al.*, 2001)

MC1 =	Capability of customizing products at low cost
MC2 =	Capability of customizing products on a large scale
MC3 =	Capability of translating customer requirements into technical designs quickly
MC4 =	Capability of adding product variety without increasing cost
MC5 =	Capability of customizing products while maintaining a large volume
MC6 =	Capability of setting up for a different product at low cost
MC7 =	Capability of responding to customization requirements quickly
MC8 =	Capability of adding product variety without sacrificing overall production volume
MC9 =	Capability of changeover to a different product quickly

According to Kakati (2002) the success of MC goes beyond technology. The application of design principles for MC can help generate a large number of variants in an effective manner cost wise and time wise. However, what is more important is to "bridge the gap between the customers and company, and increasing customers' experience" (Kakati, 2002).

2.5   Economies of Scale Versus Economies of Scope

The main concept behind mass production is to standardize as much as possible the processes, the parts used and the output production. This in turn minimizes the setup times and cost of production by promoting division of labor. The aim is to minimize the cost per product as the volume of production increases. In that case the company or factory will be experiencing economies of scale. However, in low to medium volume production, where the production

quantity cannot justify the investment, MC comes in place where customers are in that case

willing to pay more because their special needs are satisfied. Tseng and Jiao (1998) believe that

this is the area where MC provides a great advantage in business competition. In other words,

whenever, the volume of production is low, the loss in efficiencies of mass production is

compensated by the extra value-added to the product gained by customization, which is referred

to as Economies of scope. There is a clear tradeoff between both economies of scale and

economies of scope. However, if a company is capable of increasing the production volume and

pace of production, while maintaining the same level of customization, it will experience a

greater benefit.
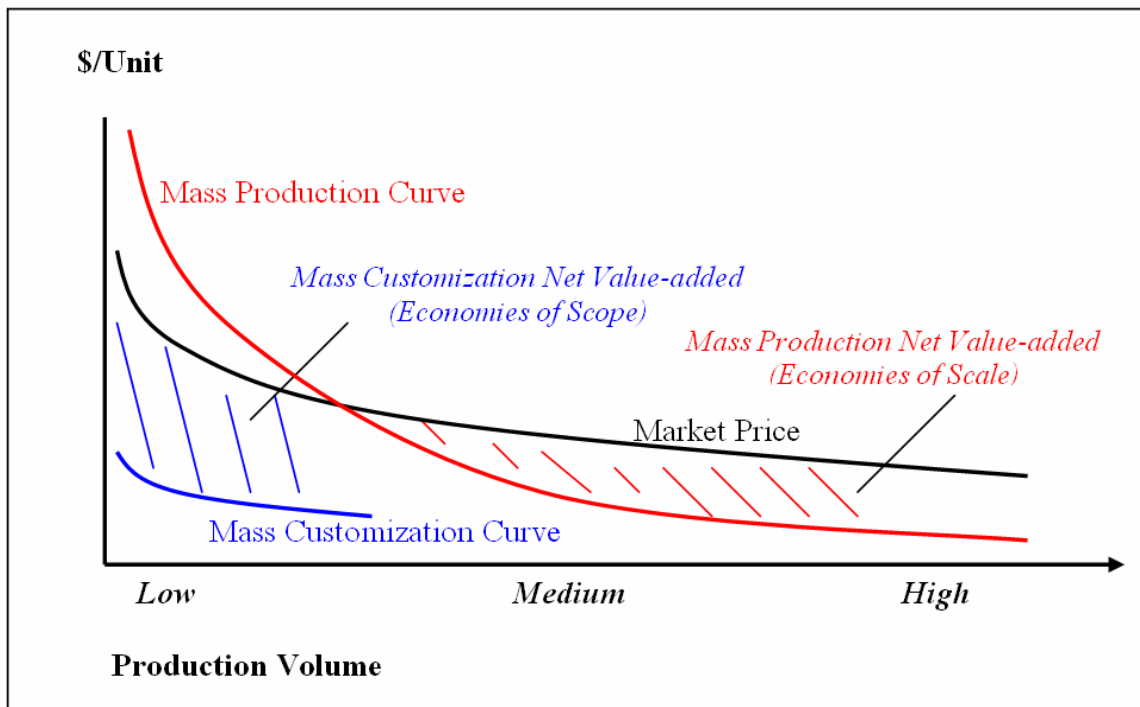
Figure 2.7 Mass customization Economic implication (obtained from Tseng and Jiao (1998)).

The diagram in Figure 2.7 indicates two cost curves, one for mass production and the

other for MC. Having the price that customers are willing to pay as a reference curve, the

tradeoff between the benefits of Economies Scale and Economies of scope are demonstrated, as a function of the production volume. The main goal of any industry that provides products or services is customer satisfaction; as the customer is the source of continuation of the business. By customizing a product or service we are contributing to the customer satisfaction, thus adding to the quality of the product or service. In some cases the value-added of a product due to customization can be considered as a quality attribute. The idea of MC is to benefit from the value-added to the product due to customization without suffering much from the inefficiencies of departing from mass production.

<div align="center">

2.6   <u>Product Architecture</u>

</div>

In order to customize a product efficiently, we have to build a product architecture that defines the universe of benefit that can be provided to a customer and; within this universe how many permutations of functionalities can be generated. Anderson and Pine (1997) define this architecture as a modular schema that consists of several common components and linkages that are capable of producing several combinations of products. Each combination offers different types of functions depending on the individual customer's need. The authors also define this scenario using a capturing example; "LEGO" (Lego the building blocks for children). In this case they define the Lego bricks as the common building blocks and the snapping ends of those bricks as the linkage system. According to Anderson and Pine (1997), in any product architecture those two elements (the building blocks and the linkage system) must be standardized. Without standardizing those two elements we can never efficiently achieve mass customization. "Modularity is the key to mass customization in product development" (Pine, 1998).

Product architecture is also named as Product Family Architecture PFA, which has a Product Family Design PFD. A product family is a set of products that have common technologies. This communality is picked up and built into a product platform that is used to create a variety of products which fosters FBD (Meyer *et al.*, 1993). According to Pine (1998), PFA means "the underlying architecture of a product platform, within which various product variants can be derived from the basic product designs to satisfy a spectrum of customer needs related to various market niches". This implies that for a PFA to be good it should have a generic architecture that is capable of employing commonality in such a way to produce a large family of successful permutations of designs, to a common product line structure. That will offer a wider variety of the same product to fit the ever changing taste and demand of customers (Tseng and Jiao, 1998).
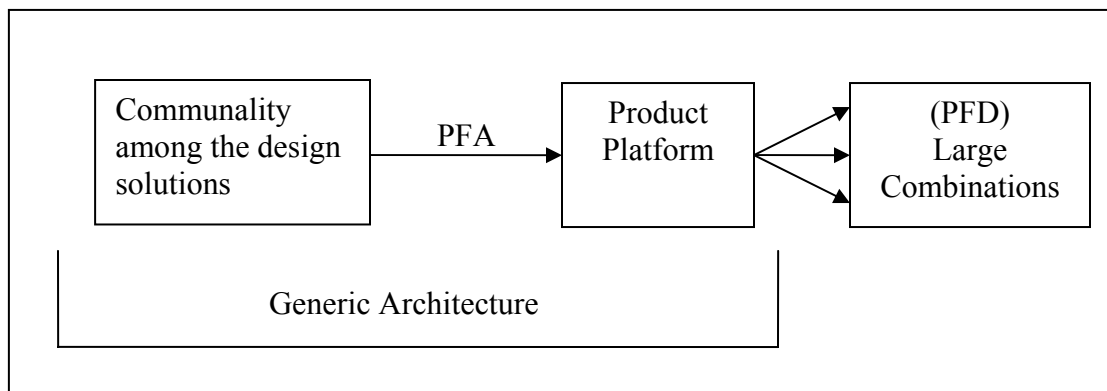
Figure 2.8 Generic architecture to produce a wide variety of designs.
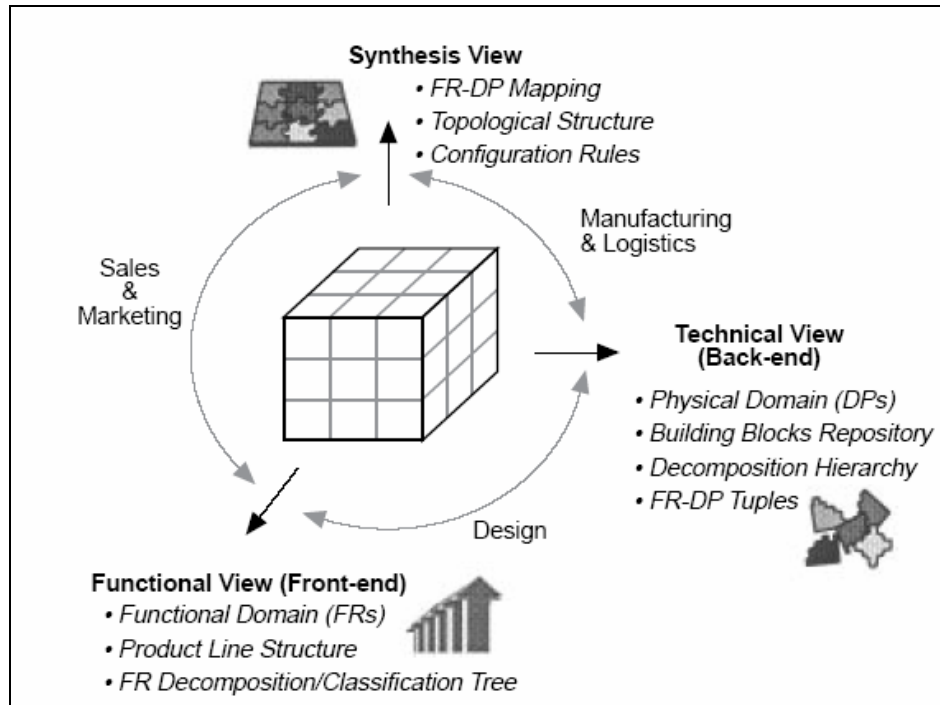
Figure 2.9 Structural Implication of a PFA (obtained from Tseng and Jiao (1998)).

2.7 Agile Manufacturing Versus Mass Customization

MC can sometimes be described as a tool to achieve Agility. That is industries, especially

in manufacturing, that apply MC principles, are better equipped to become agile.

2.7.1 Agile Manufacturing

DeVor and Mills (1995) define agile manufacturing (AM) as "the ability to thrive in a

competitive environment of continuous and unanticipated change and to respond quickly to

rapidly changing markets driven by customer-based valuing of products and services". This

definition highlights that AM needs rapid realization of product and its production process,

flexible manufacturing system, distributed decision support system, and distributed enterprise

integration. Brown and Bessant (2003 state that AM "involves being able to respond quickly and

effectively to the current configuration of market demand, and also to be proactive in developing

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and retaining markets in the face of extensive competitive forces". The importance of AM can be also explained as " … a response to competition in environments characterized by unpredictable change, so having the ability to vary capacity, respond to sporadic changes in demand, mass customize at the cost of mass production, and compete with both mass and custom markets is crucial" (Yusuf *et al.*, 2003).

2.7.1   Flexible Manufacturing

A flexible manufacturing system (FMS) is a flexible automated system that involves several machine tools, especially numerically controlled (CNC) machines that are joined together by a material handling system. All those machine activities are monitored and controlled by a central computer or PLC. The flexibility of the system enables to manufacture a wide range of different or unique products in small quantities or batch size production. FMS typically serves the manufacturing of over sized parts or components that might be a one off product. Lean manufacturing has been introduced to FMS to improve the efficiency and flexibility of the system and cut waste and lead time. However, FMS is still a far way from becoming a Mass Customization Manufacturing MCM system, as far as the number of variants generated, response time, and flexibility of the system are concerned (Berry and Cooper, 1997).

The traditional concept of FMS holds four main components: volume flexibility, manufacturing flexibility, mix ratio flexibility, and delivery flexibility.
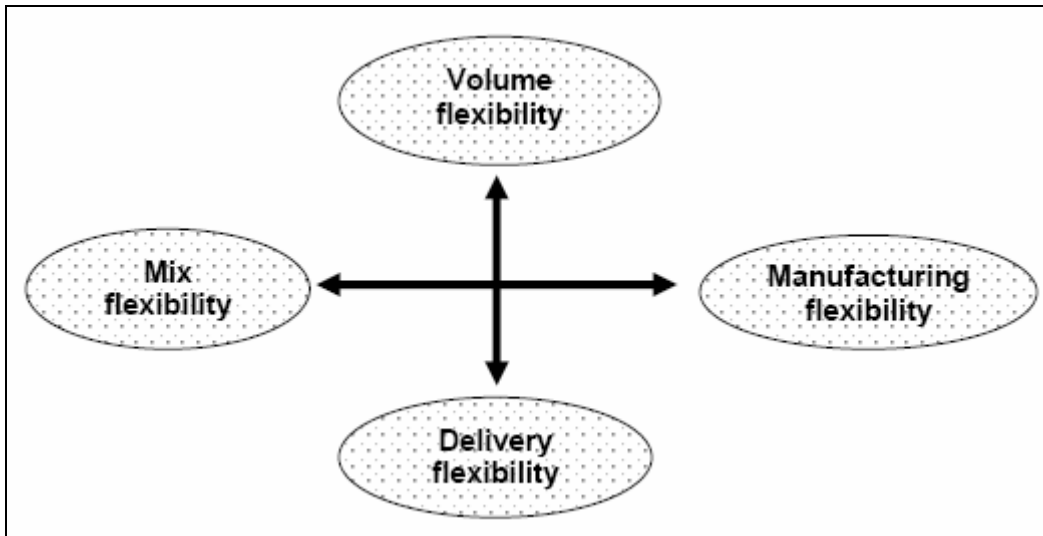
Figure 2.10 Four components of the traditional FMS (obtained from Koste and Malhotra (1998)).

According to Berry and Cooper (1997) there is a rising literature that is pushing FMS support an increased product variety system. However, there is a miss-alignment problem between the manufacturing capability and the market demand. More market research is needed in concurrency with development efforts in the FMS. There is no point of increasing the product variety unless there is a specific corresponding markets demand for it. The axes in Figure 2.11 show the batch sizes for a low production volume versus market price sensitivity. High price sensitivity refers to the customer being reluctant to purchase a product upon a slight increase in price. Low price sensitivity refers to low customer reaction upon slight price fluctuation. The diagram demonstrates the case where an increased product variety system in a FMS is mostly encouraged.
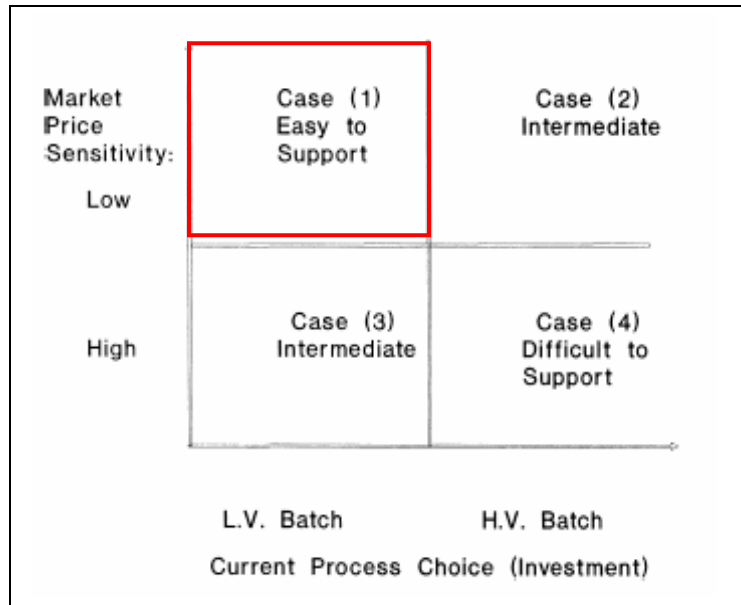
Figure 2.11 Product variety strategies for low volume products (obtained from Berry and Cooper (1997)).

Typically an increase in product variety is expected at an extent to increase the production costs and thus the selling price. The higher the batch volume the harder is the implementation of an increased variety system. Therefore, the implantation of an increased variety system would be most favorable in an environment of low batch size and low market price sensitivity.

2.7.2 Linking Agile Manufacturing to Mass Customization

The relationship between both paradigms can sometimes be confusing. "There seems to be no firm agreement as to the definitions for, and major difference between, the paradigms of mass customization and agile manufacturing" (Brown and Bessant, 2003). For example, Da Silveira *et al*. (2001) mention agile manufacturing as being a feature within their summary on MC. Brown and Bessant (2003) suggest that both AM and MC are not mutually excusive paradigms. On the other hand, they argue that MC is best described as a powerful example of a

firm's ability to be agile. It can be concluded that MC is an industrial concept that contributes in achieving agility. It has been generally noticed that agile manufacturing is mostly mentioned whenever referring to product development and production planning. However, MC usually refers to an ongoing production line that has been designed to produce a diversified family of products. Our main focus in the coming chapters will be on the implementation of MC in the manufacturing industry rather than achieving agility.

According to Qiao *et al*. (2003) in an FMS it is very important to achieve a prompt response when dealing with constantly changing demands while keep into consideration the "product costs, quality and reliability to form the flexibility in an agile MCM system".
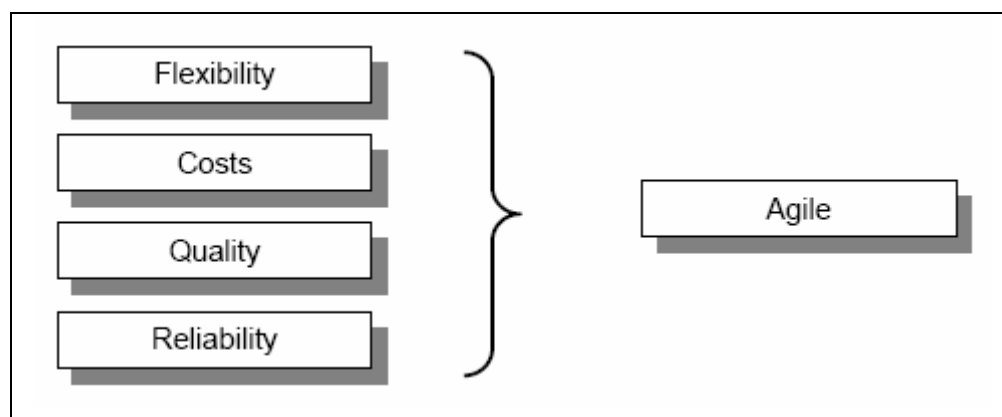
Figure 2.12 Flexibility for MCM – agile (obtained from Qiao *et al.,* (2003)).

2.8   Concurrent Engineering

The essence of Concurrent Engineering (CE) is concurrency and integration (Sohlenius, 1992). Concurrent Engineering has been considered as a very effective method in reducing the product development lead time, and in the meantime achieves an overall cost saving.

The idea behind CE is that the "product design and process design engineering must be done simultaneously and symbolically, *i.e.,* a continual to and fro between design and

manufacture. The synergy between design and manufacturing produces a better and simpler product which is easier to manufacture and thus cheaper to produce, and in the meantime maximizes customer value, thus meeting the competitive challenge" (Tseng and Jiao, 1998).

However, to be able to implement MC a third element needs to be integrated into the product development process. This element is the consumer; where the consumer in a way participates in the early stages of product design. This involvement of the customer in the design and production stage means that the customer becomes a "prosumer" as described by futurologist Alvin Toffler in his book, "Future Shock" (1970). The "prosumer" is producer and consumer in concert, defining and producing the product in collaboration with manufacturer.

2.8.1 Product Development Cycle

Product development and realization is the most important phase in the product life cycle. The product life cycle starts from an existing need, followed by a functional analysis, an idea for a solution, a preliminary design, design iterations while maintaining the aspects of concurrent engineering, developing a prototype, testing the prototype for functionality and overall performance, sampling the market, venturing into production, up to the disposal, recycling or replacement of the product. The initial phase, which is before venturing the market, is the most important part of the product life cycle. Companies dedicate a large portion of their budget on R&D because one mistake or misconception during the design and prototyping phase can cause humongous losses and sometime bankruptcy once the product has been launched into production. One the other hand, one extra clever thought incorporated into the design phase of the product can give a the company a considerable competitive edge. During the design phase many aspects of the product must be taken into consideration in parallel or in concurrency.

Therefore, "concurrent engineering is an ideal environment for product development" (Huang, 1996).

2.8.2 Design for X

The purpose of CE includes, reducing manufacturing cost, minimizing the lead time, reducing the throughput time, increasing the flexibility, assuring quality, increasing reliability, improving production efficiency, promoting a brand name, inducing simplicity, and many other aspects.

Designers can get confused and lost when trying to come up with an ideal design. There may be so many features, properties, and musts that have to be taken into consideration. Sometimes an artistic touch is on the of list properties to be taken into account. Therefore, there is a need for a design team that operates in concurrency to map together all the interacting issues that need to be integrated into one single complete design. "… Design for X (DFX) is one of the most effective approaches to implementing CE" (Huang, 1996). Typically, all the necessary aspects are listed and sorted in order of importance, and then the vital elements are focused upon. According to Huang (1996) it is usually a limited number ranging "5-9 primary factors". This does not mean that the other aspects are omitted, but the priorities are established in case of clashes. The DFX factors have been categorized, by Huang (1996) into two categories: Design for life cycle, and Design for competitiveness. The former includes the vital elements that are needed for the product to be functional, and the latter, is provide confidence that the product will sell.

Some of the major factors included in a "Design for Life cycle" category:

- Design for dimensional control.

- Design for functionality.

- Design for Manufacturability and Assembly (DFMA).

- Design for logistics (design for Supply Chain high performance).

- Design for material handling and procurement.

- Design for Inspect-ability, quality control.

- Design for maintainability and serviceability or accessibility.

- Design for Reliability and durability.

- Design for Electromagnetic control.

- Design for ease of disassembly, recycling or disposal.

- Design for cost (affordability) and profitability

Some of the major factors included in a "Design Competitiveness" category:

- Design for Quality.

- Design for flexibility.

- Design for Modularity.

- Design for Optimal environmental impact.

- Design for sales and marketing.

- Design for aesthetic appearance.

Some of the major factors that have been lately stressed:

- Design for Quality Control (Six Sigma)

- Design for upgrading and innovation.

- Design for Ergonomics and Safety

- Design for mass Customization (DFMC)
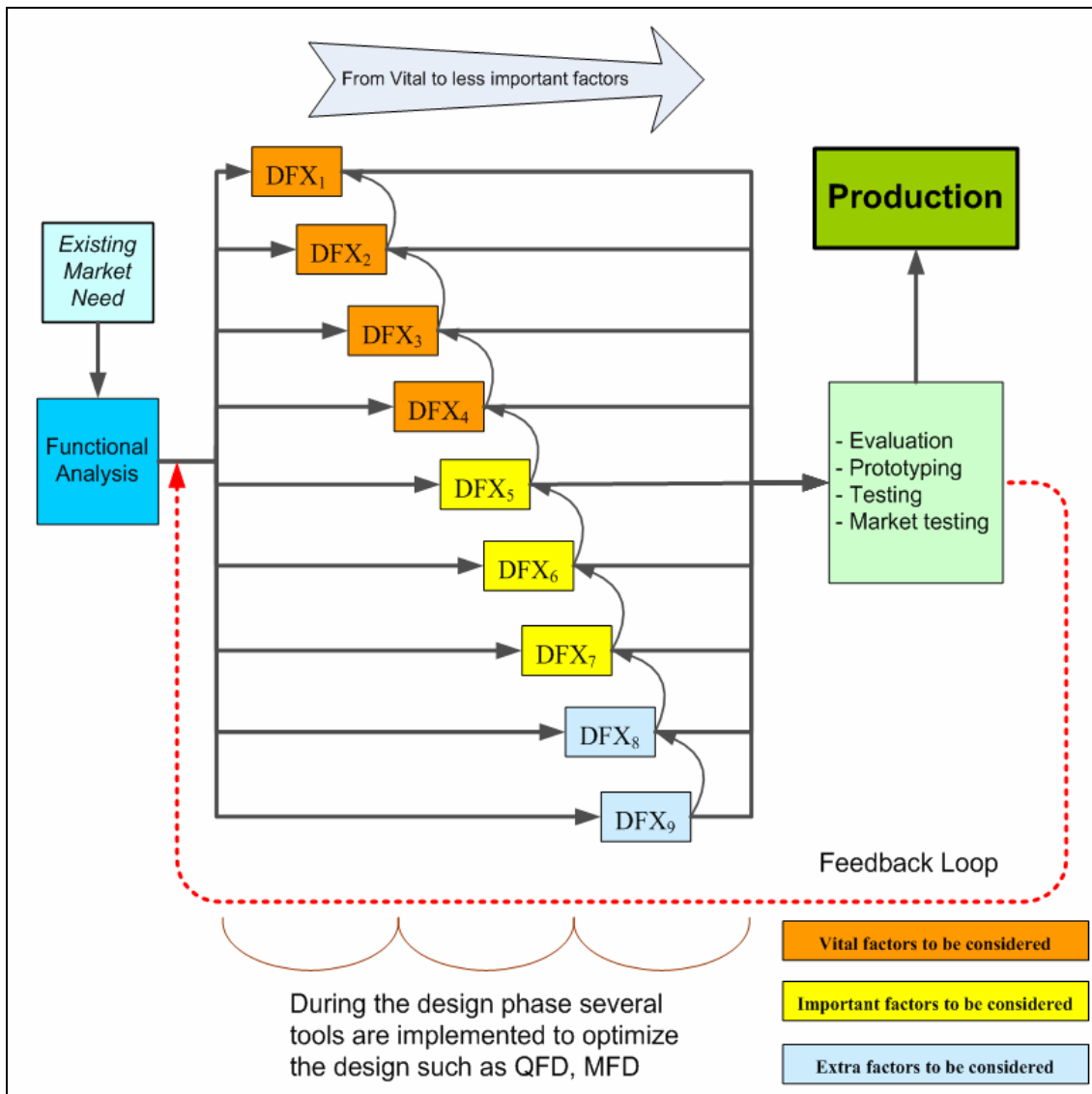
Figure 2.13 Aspects of concurrent engineering during the product development phase.

As shown in Figure 2.13 the product development process starts with a need followed by a functional analysis, design phase, prototyping and testing, evaluation, and then finally production. During the design phase, most of the aspects of CE are taken into consideration in parallel, however, the priority is always given to the vital elements followed by the less important element; ending with supplementary features that would be useful, however not really

necessary. (DFX_1, DFX_2, … DFX_k) represent the elements of CE in order of most important to least important. During the design phase a preliminary design is made taking into consideration (DFX_1) and then it is moved on to (DFX_2). The design is modified according to the requirements of (DFX_2). Before moving onto (DFX_3), the design is returned to (DFX_1), to check that after the modification it still meets the requirements of (DFX_1). This process is repeated until (DFX_k) is reached, where the design would be finalized. The next step is to produce a functional model or prototype for testing. The model is evaluated, and the feedback is sent back to the design phase to make the necessary modifications. After several iterations a final solution is then reached that is ready for production. Technology advances help reduce the lead time for each iteration, such as the rapid prototyping and rapid tooling. A shorter overall lead time for product development is an important competitive edge in the market.

2.8.3 Design for Mass Customization

Design for Mass Customization (DFMC) is extension to the DFX family. It has recently been adopted, when Tseng *et al*. (1996) coined the term "DFMC". DFMC deals with MC from a product development standpoint. It is an extension to the traditional methods of product development techniques. However, instead of dealing with a single standard product that satisfies all the requirements and design aspects, it paves the way for the design of product families. The core of DFMC is "a generic platform for a Product Family Architecture (PFA) as a generic product platform for product differentiation in which individual customer needs can be satisfies through systematic decisions of developing product variants instead of starting from scratch with each individual customer" (Jiao, 1998). According to Jiao (1998), the goal of DFMC is to

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"extend the traditional boundaries of product design" to encompass a wider market scope

including sales, marketing, distribution and services.
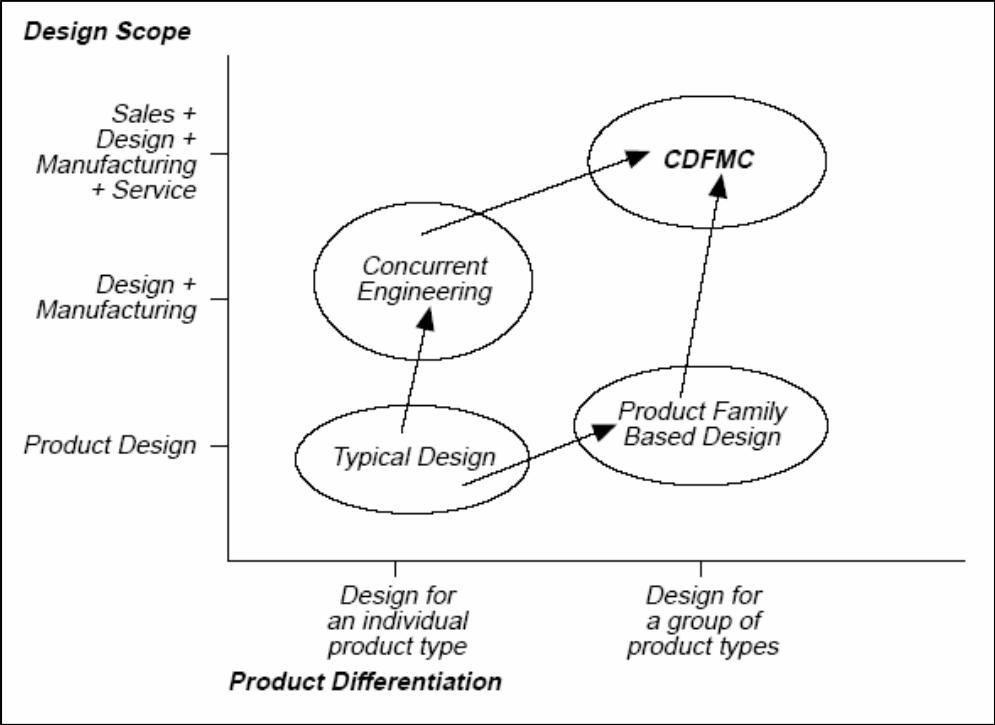
Figure 2.14 shows the influence in introducing a product Family Based Design (FBD) in
realizing Concurrent Design for Mass Customization (CDFMC) (obtained from Jiao (1998)).

The idea, as shown in Figure 2.14, is to shift the traditional concept of CE from an

integral design to a modular design that generates a family of products rather than an ideal

individual product.

2.9 The Impact of Technology on Mass Customization: Additive Manufacturing

2.9.1 Rapid Prototyping

Rapid Prototyping (RP) is a turn key technology that changed the way we conceive things in the industry. It is sometimes referred to as "Additive Technology", "Layered Manufacturing or "Solid Freeform Technology". This technology enables the manufacturing of non-traditional parts having relatively complex geometries directly from CAD designs. It has paved the way for a new industry that is much more efficient and can realize manufacturing achievements that were traditionally thought impossible. RP accelerated the product develop cycle, thus minimizing the lead time to launching a new product to the market. RP also contributed to research by providing scientists with the need of one-off parts, which are unavailable in the market, to run their experiments.

When the RP methods became more sophisticated in terms of accuracy, time and quality of materials being used, the term "Rapid Tooling" (RT) emerged. RT means the incorporation of Additive Manufacturing methods in the fabrication of the metallic dies for casting or injection molding and so forth. There are two method of using RP to produce tools for manufacturing purposes: Direct Tooling and Indirect Tooling. The former method involves directly building permanent molds by using metal RP machines. Examples for that would be Direct Metal Deposition DMP machines such as Laser-Engineered Net Shaping (LENS) and Laser Forming (LasForming) (Kelly, 2003; Luo *et al*., 2004). The latter method uses parts that have been built by using non-metal RP machines to produces the temporary patterns from which permanent tools will be fabricated. Traditionally those tools were realized using CNC machines and skilled craftsmanship which resulted in a relatively high product development lead time; especially

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when several iterations were necessary. The RP technology reduced the lead time of tool

fabrication and reduced the human error involved during the carving process. One misfortune is

that many skilled craftsmen and artists lost their jobs as a result of this new technology.

The latest technologies such as rapid prototyping have inspired the concept of Rapid

Manufacturing (RM). Rapid prototyping has emerged in the first place because there was a need

for a new technology that gives a boost to the development and realization of new in terms of

time and cost

This technology is currently in a developing phase. Everyday, there are new machines

and approaches that are more efficient, precise and capable than the previous ones. This lead

some industrialists especially in the manufacturing domain to consider the use of the additive

technology for machines that act as workstations in production lines. This concept is referred to

as "Rapid Manufacturing" (RM) "Additive Manufacturing", "Solid Freeform Fabrication"(SFF),

or "Tool-less Production". The concept is still being developed as there are still many obstacles

such as the precision of fabrication, setup costs and others.
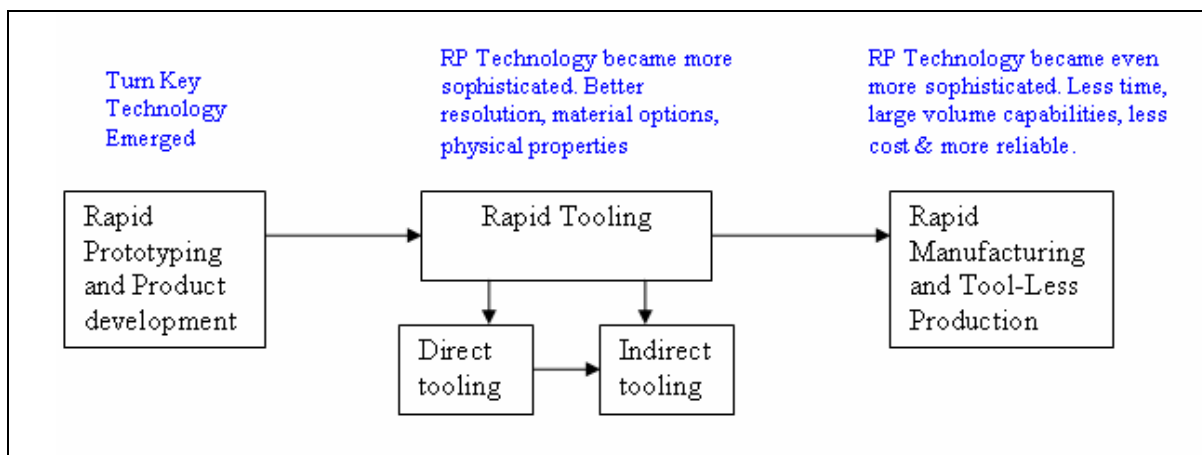
Figure 2.15 Evolution of RP methods and technology.

By using RM firms will acquire a relatively high degree of freedom for customizing components and products. For example, a product can consist of a housing module that can have any desired artistic shape requested by the customer. The fabrication time will be independent of shape and complexity of the design. That would be a major breakthrough in application of the MC concept.

2.9.2   The Best Candidates for Rapid Manufacturing

Manufacturers are the best customers for RM. According to the (World wide Guide to Rapid Prototyping, 2005), manufactures know best the consumers and are capable of using specialized machinery to provide the customer with object needed in short lead time. They also are experts in industrial design, materials and concurrent engineering aspects.

Statistics show that in 2003, 173,000 manufacturing firms in the US and Canada were making use of rapid manufacturing; most of whom are small firms with a little number of employees. This number is increasing by the year. The Statistical Abstract of the US recorded 306,000 manufacturing firms having one or more employees for the year 2000. 93% of these firms have less than 100 employees and 86% have sales under $5 million per year (Statistical Abstract of the US, 2003).
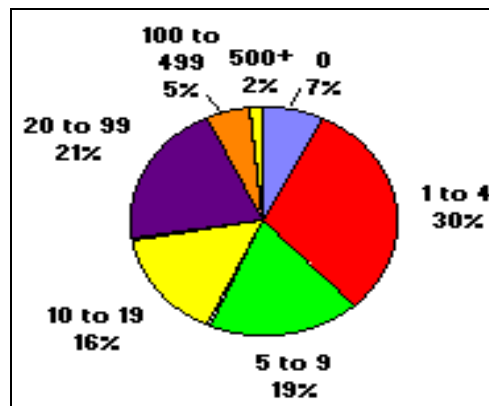
Figure 2.16 Number of manufacturing Employees (Statistical Abstract of the US, (2003)).

The (World wide Guide to Rapid Prototyping, 2005) concluded that there are likely more than a million small to medium sized manufacturing firms worldwide; most of whom would be more than willing to adopt the additive manufacturing techniques to offer better and faster personalized services. RM would allow them to venture in SFF (Solid Freeform Fabrication), which will help them provide unique characteristics to each individual customer in a record time. This lays the foundations for a new developing technology that is referred to as "tool-less production" (Bak, 2003). This technology will provide a wider potential or degree of freedom in the implementation of MC in manufacturing systems.

2.10   The Use of Modularity in a Mass Customization System

Customization and mass production are sometimes viewed as opposing concepts: the former targeting economies of scope and the latter seeking economies of scale and standardization. The MC concept can be viewed as a paradox that is hard to conceive how would encompass both principles. However, there are techniques and rules to realize that. According to Pine "the best method of achieving mass customization – minimizing costs while maximizing individual customization – is by creating modular components that can be configured into a wide variety of end products and services" (Pine, 1993). Modularity is one of the major principles that can help achieve an MC system. According to Arnheiter *et al*., (2005), there is a lack of agreement on a clear typology for modularity, especially between researchers and managers. Whereas a clear description of typology for soft modules exist, the literature on hard modules is not enough. The most commonly type of hard modules used are "manufacturing modules"

(Arnheiter *et al.*, 2005), which are the ones we will be mainly dealing with throughout this research.

There are many definitions for modularity in the literature. Each authors or researcher tends to describe it in light of his or her experience or research involvement. It is like every single definition is pointing to the same ideology but from a slightly different angle. "A module is the conceptual grouping of components. Modularity is the concept of decomposing a system into independent parts or modules that can be treated as logical units (Pimmler and Eppinger, 1994). From a manufacturing angle, "Modularity is regarded as a manufacturing strategy to effectively organize complex products and processes" (Tu *et al.*, 2001). Generally speaking modularity can be described as "the degree to which a system's components can be separated and recombined" (Schilling, 2000).

Tu *et al.* (2004) conducted a study to define Modular-Based Manufacturing Practices (MBMP). After researching the literature it has been concluded that modularity in a manufacturing environment does not only have to apply to the units produced. The authors define MBMP as a set of initiatives that enable a firm to establish modularity in several aspects of the company including product design, production process design, and organizational design or dynamic teaming.

1) The <u>product modularity</u> involves the breaking down of products into a range of separate structural and functional modules that have standard linkages.

2) The <u>process modularity</u> is about grouping processes and sub-processes into standard process modules that can be flexibly re-sequenced or accept additional modules to easily and quickly respond to different unexpected requirements. Process modularity enable the firm to conduct some effective MC principles such as DPD (Delayed product

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Differentiation) and process postponement (postponement of the decoupling point) which

will discussed in later sections.

3) <u>Dynamic teaming</u> is similar to product and process modularity in a way that it considers

forming human resource into module of flexible teams that can easily serve differing

tasks and various process arrangements. This concept is very similar to lean principles.

In lean manufacturing the flexibility of working teams enable the firm to maintain most

of its efficiency by minimizing waste of time, material and effort particularly when

unplanned changes occur (Tu *et al*., 2004).

"Product modularity" shall be further explored from a manufacturing standpoint in a

product development phase. The following sub-sections will describe a common technique that

product designers use when designing the modules for a new family of products such as

"Modular Function Deployment" (MFD) and Module Identification Matrix (MIM). MFD deals

with economic aspect of the product architectural design (Erixon *et al*., 1996a). However, those

techniques require adequate technical experience in field and an adequate understanding of the

market demand and customer requirements.

2.10.1   Modular Function Deployment

Modular Function Deployment (MFD) is an extension to Quality Function Deployment

(QFD) in a product development phase. Dealing with the economic part of product architecture,

the product designers try to map the functional needs to physical structures that will serve the

purpose. There are several factors that are taken into consideration during the design phase such

as design for X which has been addresses in sec. (2.7.2). QFD helps determine the set

components needed that will fulfill all the functional requirements, while the MFD part helps in

determining how to combine different sets of components into separate groups or modules. Those modules contain linkages or interfaces that will allow them to build up and form a finalized product. The interface between modules can consist of structural connecting points, data or signal transfers points, energy transmission, motion transmission, heat transfer, wireless transmission or others.

The following are the five steps for MFD as it has been describe by (Ericsson and Erixon, 1999):
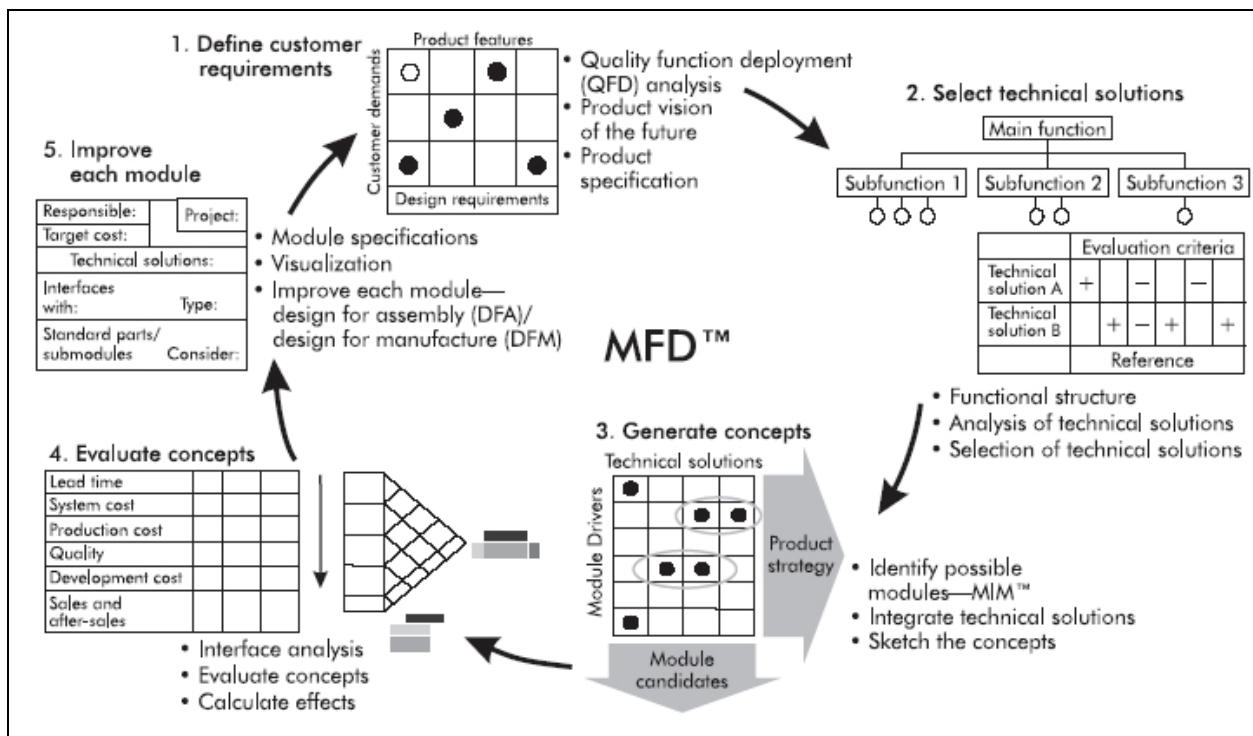
Figure 2.17 The five steps of Modular Function Deployment. The circle illustrates that design work is an iterative process (obtained from Ericsson and Erixon (1999)).

STEP 1: Define customer requirements:

This step involves the QFD analysis which is to understand the need of the customer and trying to translate those requirements into functional requirements that will be mapped to technical or structural properties of the product. This step is generic to any standard integral

product. The only difference is that in MFD a modularity column is included to "establish the right mind-sets". (Ericsson and Erixon, 1999)
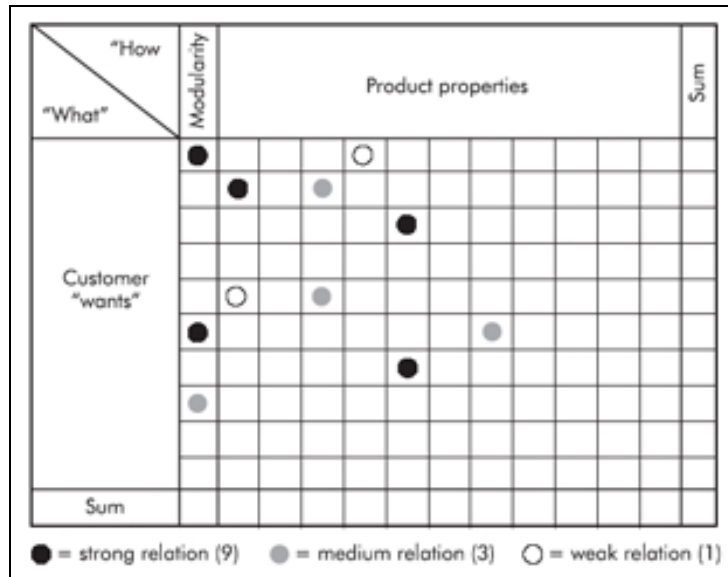
Figure 2.18 A simplified QFD matrix showing the relation between customer wants and product properties (obtained from Ericsson and Erixon (1999)).

STEP 2: Select technical solutions:

This step includes breaking down the product into set functions where a design team can work together on mapping technical solutions to each function. It is referred to as "functional decomposition". Typically a Pugh Matrix is used to determine the different alternative solution and how well they address the functional requirements.

Figure 2.19 A Pugh Matrix is used for functional decomposition (obtained from Ericsson and Erixon (1999)).

STEP 3: Generate a modular concept:

This step it distinguishes MFD from the traditional QFD process. Its purpose is to introduce module solutions for each of the technical solutions, by using "module drivers". The module drivers are a set of reasons for which it would be better to create modules as a technical solution. A "Module Indication Matrix" MIM (Eggen, 2003) is used to visualize the strength of using each module driver for the set of technical solutions that were generated in Step-2.
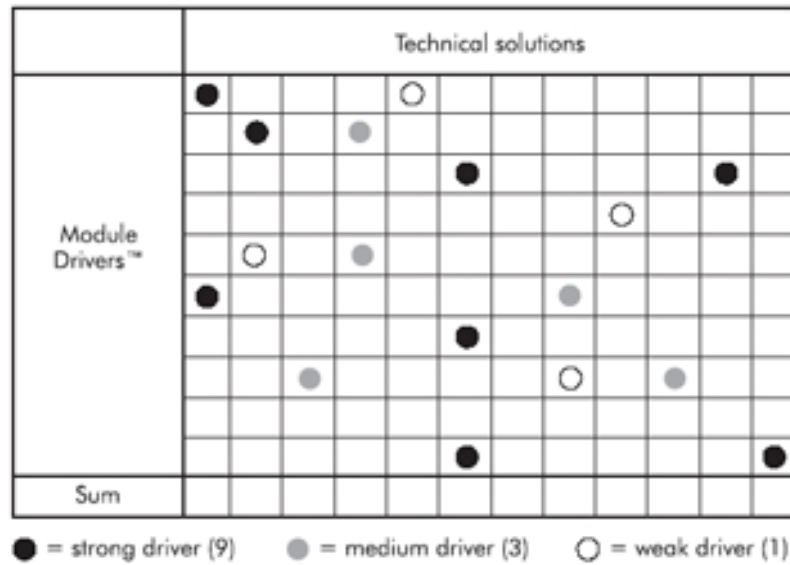
Figure 2.20 A Pugh matrix is used for functional decomposition (obtained from Ericsson and Erixon (1999)).

Table 2.3 Modularity drivers, linked to different functions of a company (obtained from Eggen (2003)).

Product development and design	Carryover	A part or a subsystem of a product that most likely to any design changes during the life of the product heavy investment in production technology.
	Technology evolution	Parts that are likely to undergo changes as a result of changing customer demands or technology shift. It will be important to accommodate the interfaces so that new technology can be introduced and replace the module in question.
	Planned product changes	Parts of the product that the company intends to develop and change.
Variance	Different specification	To handle product variation and customization effectively, a designer should strive to allocate all variations to as few product parts as possible.
	Styling	Styling modules typically contain visible parts of the product that can be altered to create different variations of the product.
Production	Common unit	Common unit is similar to the shared functions across products described by Dahmus et. al., i.e. parts or subsystems that can be used for the entire product assortment.
	Process and/or organization	Parts requiring the same production process are clustered together. For example, all parts requiring welding may be moved into a single module to enable atomization.
Qualility	Separate testing	to final assembly may contribute to significant quality improvements, due to reduced feedback times. Purchase Supplier availability Purchase standard modules to enable atomization.
Purchace	Supplier availability	Purchase standard modules from external vendors
After Sales	Service and maintenance	Parts exposed to service and maintenance may be clustered together to form a service module to be able to quickly replace and repair/replace it.
	Upgrading	Give customers the possibility of changing the product in the future
	Recycling	Easily recyclable material can be kept in separate recycling modules.

Table 2.3 shows that that there are several incentives for which it is preferable to form modules that encompass various functions and components. Not all the drivers are intended for MC. Only the "Variance" has a direct link with MC as its purpose is to allow the mix and match of various modules to produce a range of variants. This research partially deals with determining the optimal number of module per product that will in turn determine the degree of customization or size of variant generation.

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Ericsson and Erixon have introduced another factor which helps determining a suitable number of modules required for a particular product, which is the lead time of assembly as a function of the number of assembly operations required. This could be used as constraint or guide line when determining the number of modules required for MC purposes.
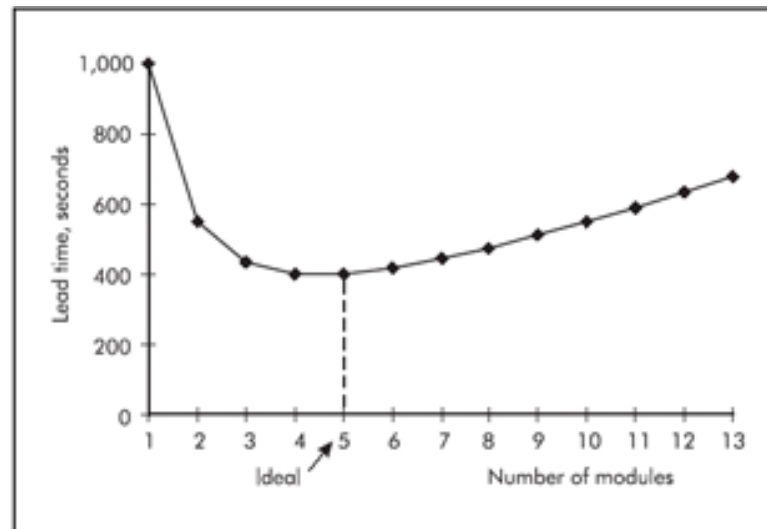
Figure 2.21 Lead time in assembly as a function of the average number of modules in a product (obtained from Ericsson and Erixon (1999)).

Ericsson and Erixon found that the "… Minimum lead time is achieved when the number of modules is equal the square root of number of assembly operations in the average product" (Ericsson and Erixon, 1999).

STEP 4: Evaluate a modular concept:

This step is about evaluating the modules that have been selected in the previous step. The module selection can be compared to an existing or a typically known module arrangement to check if there has been any improvement in the performance. By performance, we mean system costs, lead time, variant flexibility and others. Lead time in an assembly is a function of the average number of modules in a product. One of the main aspects of forming a module,

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which affects the performance of the system, is the interface or connection points. Ericsson and

Erixon have proposed an interface matrix to better evaluate the relationship between the various

modules and each other. In their description the distinction was made between two types of

assemblies: "Hamburger" and "Base Unit Assembly" (Ericsson and Erixon, 1999).
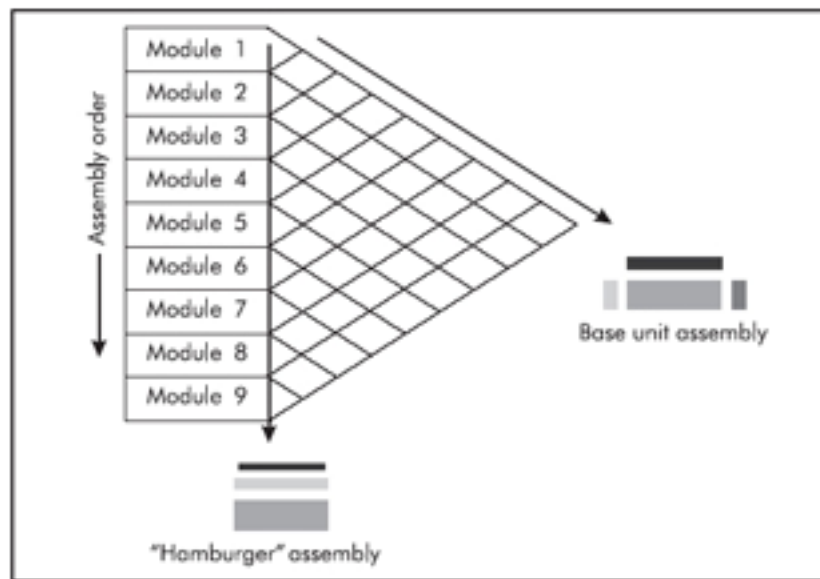
Figure 2.22 Identification Matrix (obtained from Ericsson and Erixon (1999)).

STEP 5: Optimize modules:

Once the modules have been constructed they form the basis of the product platform. The

modules can then be treated as individual units that can be improved in an iterative fashion until

optimized.

Eggen (2003) expanded the MFD into a 7-step process. More tools were included starting

from the functional decomposition step, where function chains were created as sequential versus

parallel. Heuristics were used to identify modules from functional models for product

architecture. The heuristics used were the Dominant flow, Branching flow, and Conversion-

transmission (Stone *et al.*, 2000).

The Dominant flow heuristic analyzes a set of sub-functions flow that is non- branching from an initiation point throughout the system until the exit point or until it is transferred to another flow. The modules identified do not have parallel interface.

The Branching flow heuristic analyzes modules that have parallel interfaces and that typically link a module to the rest of the product. The module is identified where flow branches into "limbs" of parallel function chain where each limb is a set of sequential function chain that potentially constitutes of a module.

The Conversion-transmission flow heuristic groups the sub-functions that are involved in converting one type of flow to another. For instance, a car dynamo is a module that encompasses a set of sub-function that are responsible to transfer a motion flow into electrical energy flow that will be interfaced via wiring ending up charging the car battery (Stone *et al.*, 2000).
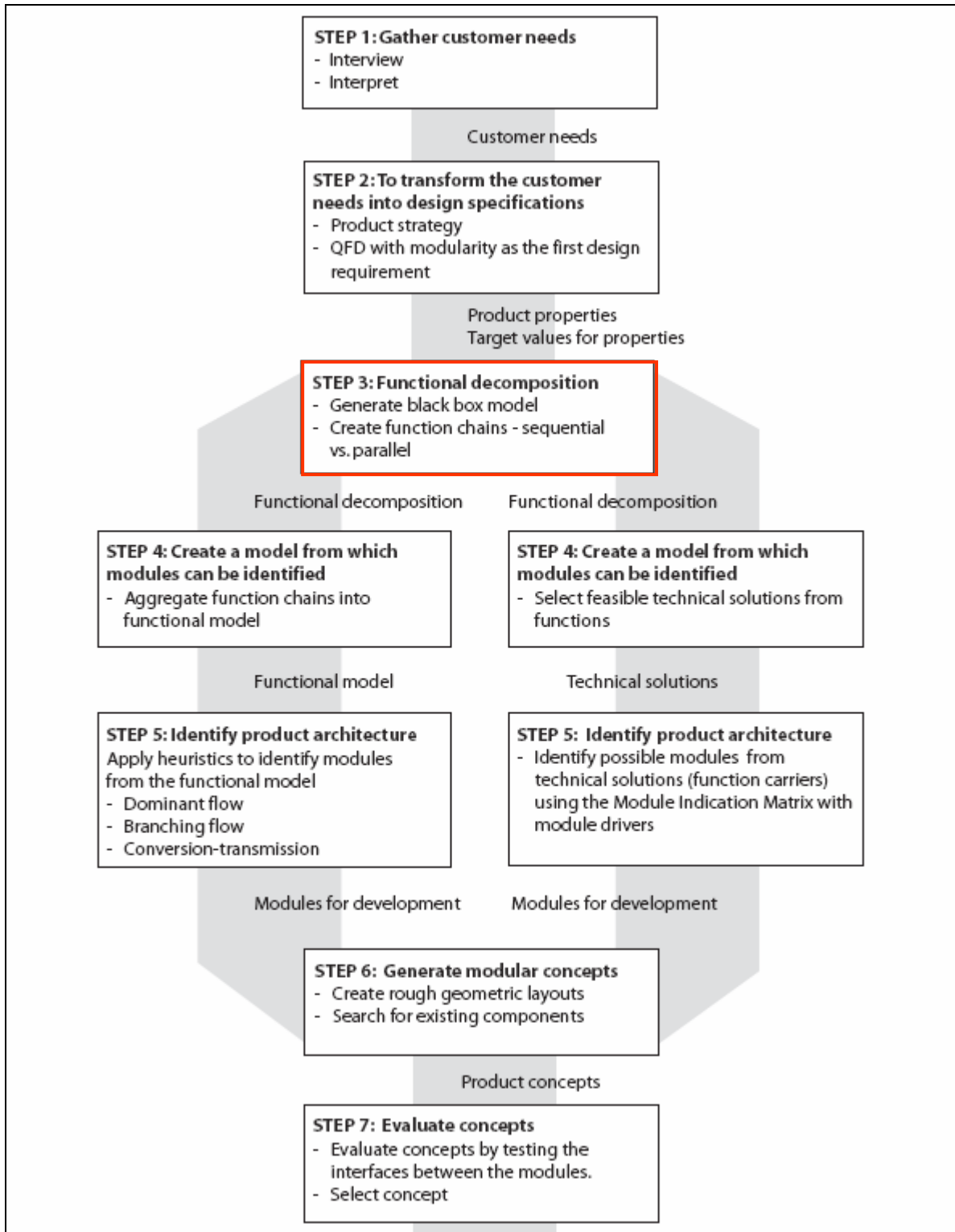
Figure 2.23 Model for modular concept generation based on MFD approach (obtained from Eggen (2003)).

2.10.2   Analytical Formulation for the Optimization of Modular Architecture

Fujita *et al.* (1999) developed a mathematical formulation for product variety design by employing a 0-1 integer-programming method that was adopted from an optimization algorithm based on a "simulated annealing technique". The formulation targeted a cost minimization objective that regarded based and variable costs. There were three types of constraints to the mix match of modules that were considered: *Diversion Feasibility, Simultaneity, and Capacity Constraint*.

- *The Diversion Feasibility Constraint* prevents diverting modules that were initially assigned for a specific product "A" to another product "B". In that case the constraints are the modules that cannot be used for particular module slots. It is represented as follows (Fujita *et al.*, 1999):

P_i (i = 1,2 … I) represents the various product.

M^j (j = 1,2 … J) represents the different modules slots.

(k= 1,2 … K) represents the various modules that could be used for each module slot.

$$x \begin{cases} 1 \dots m_k^j \text{ module is implemented in } M^j \text{ slot of } P_i \text{ product.} \\ \\ 0 \dots m_k^j \text{ module is implemented in } M^j \text{ slot of } P_i \text{ product.} \end{cases}$$

Where, $K = \max_j k^j$

Only one module can be assigned per module slots:

$$\sum_{k=1}^{K} x_k^{j(i)} = 1 \quad (i = 1,2, \dots, I; j = 1,2, \dots, J) \tag{2.1}$$

- *The Simultaneity Constraint* regards modules that if diverted require other modules to be diverted too due to functional coupling. The formulation for that particular constraint depends on the nature of the products at stake and the complexity of the functional interrelationship of the various modules.

- *The Capacity Constraint* works on assuring that the overall capacity of the system is within the acceptable range. It starts by assigning a specific demand or supply capacity for each module, such as for example, power consumptions. In that case the constraint would be that the total power consumption of the sum of all modules would be below the overall system's power supply. The formulation is as follows (Fujita *et al.*, 1999):

$$\sum_{K=1}^{K} C_p(m_k^7) x_k^{7(i)} \geq \sum_{j=1}^{6} \sum_{k=1}^{K} C_p(m_k^j) x_k^{j(i)} \quad (i= 1,2, \ldots, I) \tag{2.2}$$

Where, $C_p(m_k^j)$ is demand or supply capacity of module m_k^j.

The total associate cost "C_t" is represented by two parts: fixed cost "C_f"part and a variable cost "C_v" (Fujita *et al.*, 1999).

$$C_t = C_f + C_v \tag{2.3}$$

The fixed cost part is represented by the following equation:

$$C_f = C_f^0 + \sum_{i=1}^{I} C_f^{P(i)} + \sum_{k=1}^{K} \sum_{j=1}^{J} C_f^M y_k^j \tag{2.4}$$

Where "C_f^0" is the hidden fixed cost that is not related to a module or product type number,

"$C_f^{P(i)}$" is the fixed cost per product type, and "C_{fK}^{Mj}" is the fixed cost per module type.

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The variable cost part is represented by the following equation:

The Total variable cost of production consists of material costs" C_v^m ", fabrication costs " C_v^f ",

and assembly costs " C_v^a ".

$$C_v = C_v^m + C_v^f + C_v^a \tag{2.5}$$

The material costs can be expressed as such:

$$C_v^m = \sum_{k=1}^{K} \sum_{j=1}^{J} C_{vk}^{mj} U_k^j \tag{2.6}$$

Where " C_{vk}^{mj} " is the material cost per unit module and " U_k^j " which is the unit number of the

product.

The material costs can be expressed as such:

$$C_v^f = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{u=1}^{U_k^j} C_{vk}^{fj} L^f(u) \tag{2.7}$$

where " C_{vk}^{fj} " is the initial unit fabrication cost of the module " m_k^j ", and " L^f " is the learning

effect in the module fabrication.

The assembly costs can be expressed as such:

$$C_v^a = \sum_{i=1}^{U^P} C_v^a L^a(u) \tag{2.8}$$

Where " C_v^a " is the initial unit assembly cost per product, and " L^a " is the learning effect for

product assembly (Fujita *et al.*, 1999).

The cost formulation, however, lacks the benefits associated with a wider range of variant

production. The customers would value more a product that can avail more customized features.

In addition, more variants can capture wider market niches, which would contribute to the overall profit. Such criteria need to be considered during the modular architecture phase.

2.10.3   Modularization and Interface Constraint

According to Hsuan (1999), Modularization is the "opportunity for mixing-and-matching of components in a modular product design" and "the degree of modularization" is mainly dependent on the components number and the interface constraints". Hsuan categorized Modularization into four levels:

- *Component level:* is the lowest level, or smallest element of the product; they are highly standard; typically on the shelve parts.

- *Module level:* where modules are formed by combining a set of components in a certain arrangement.

- *Sub-System Level:* is an assembly of modules producing a highly customized part of the product. For an automobile manufacturer an example of a Sub-System would be a complete Gear box or engine.

- *The system level:* is the complete product after all the Sub-Systems have been assembled.

Figure 2.24 Characteristics of different levels of modularization (obtained from Hsuan (1999)).

Figure 2.24 shows that it is easier to find opportunities for modularization at the lower levels than higher level of the system where the product is almost complete. However, the component customization is better reserved for higher levels of the system to reduce the complexity involved. There was an important contribution in Hsuan's work (1999). An analytical formulation for Modularization was identified as a function of the interface constraint "δ", number of components, and the supplier buyer partnership index "α". The function $f(\delta)$ represents opportunities for modularization of the system given the parameters: δ and α.

$$f(\delta) = e^{-\alpha\delta^2} \quad (0 \leq \alpha \leq 1) \quad \text{(obtained from Hsuan (1999)).} \quad (2.9)$$

A value of one for "α" would indicate a strategic partnership between the supplier and buyer which facilitates tremendously opportunities for modularization; *i.e.,* it would maximize the "envelop of modularization". On the other hand, a value of zero for "α" refers to a "Durable Arms Length Relationship", where, for example, the buyer would purchase standard parts from the shelf.

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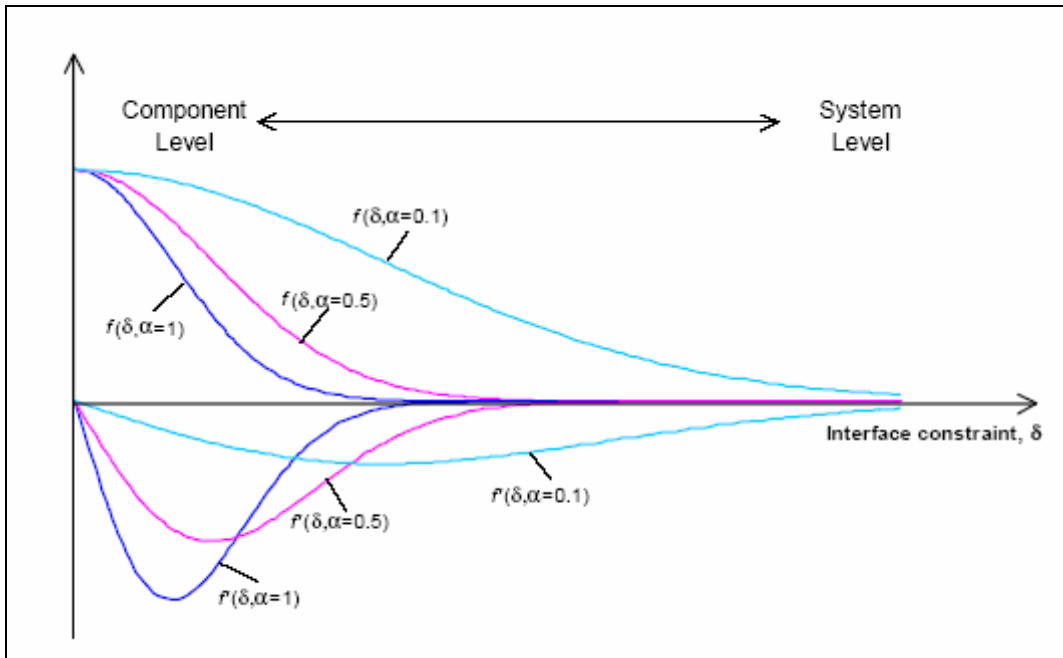
Figure 2.25 Modularization Function (obtained from Hsuan (1999)).

Hsuan (1999) introduced a method to estimate the Interface Constraint Factor δ. It can be determined by quantifying the ratio interfaces for each module relative to the overall constraints of the system. Figures 2.26 and 2.27 show an example to clarify the method. The example consists of a System A that comprised of two Sub-systems including five modules that can be decomposed into eight components.
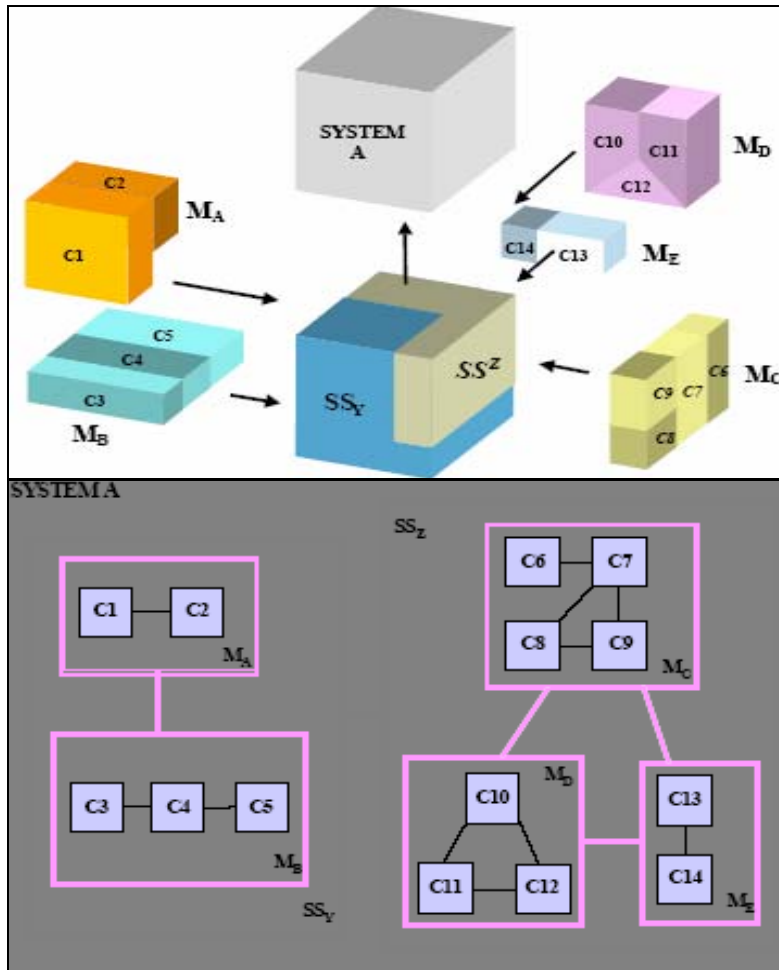
Figure 2.26 Decomposition of System A into sub-systems, modules, and components (obtained from Hsuan (1999)).
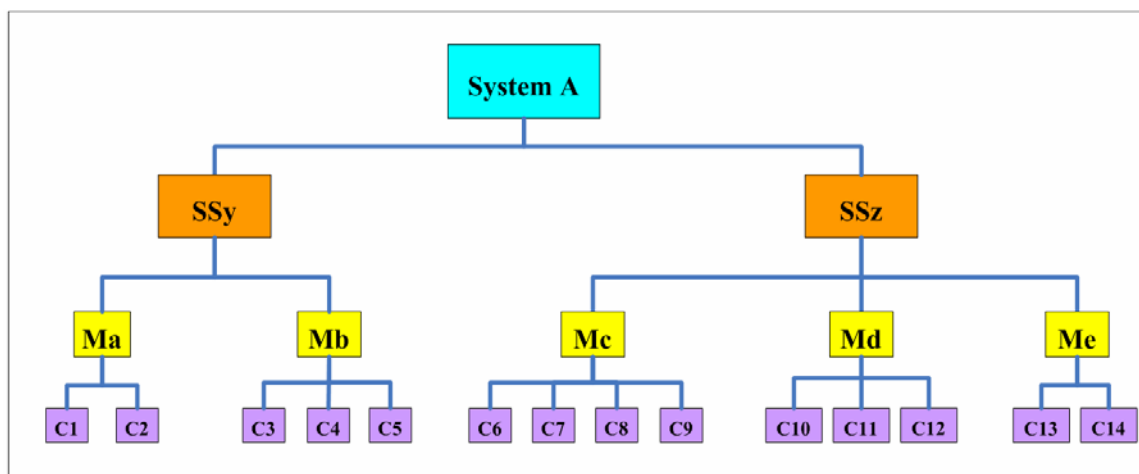
Figure 2.27 Hierarchal representation of the decomposed system (obtained from Hsuan (1999)).

As seen in Figure 2.26 each module has a set of components that are connected to each other via interfaces. Each component has a level of significance or interface weight (W_C), which is the number of interface (k_c) per component divided by the total number interfaces of all the components in the module ($\sum k_c$). The same goes for the interface weight of Modules (W_m) and of Sub-systems (W_{ss}). The formulation is as follows (Hsuan, 1999):

$$w_c = \left[\frac{k_c}{\sum k_c} \right]_m \quad , \quad w_m = \left[\frac{k_m}{\sum k_m} \right]_{ss} \quad , \quad w_{ss} = \left[\frac{k_{ss}}{\sum k_{ss}} \right]_s \qquad (2.10)$$

The interface constraint for each module is denoted by the symbol δ_m where n_c is the number of components per module. The equation is expressed as follows (Hsuan, 1999):

$$\delta_m = n_c \left[\prod w_c \right]_m \qquad (2.11)$$

The interface constraint for each Sub-System is denoted by the symbol δ_{ss} where n_m is the number of modules per Sub-System. The equation is expressed as follows (Hsuan, 1999):

$$\delta_{ss} = \sum [\delta_m]_{ss} + n_m \left[\prod w_m \right]_{ss} \qquad (2.12)$$

The interface constraint for the System is denoted by the symbol δ_s where n_{ss} is the number of Sub-Systems per System. The equation is expressed as follows (Hsuan, 1999):

$$\delta_s = \sum [\delta_{ss}]_s + n_{ss} \left[\prod w_{ss} \right]_s \qquad (2.13)$$

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The mathematical formulations presented by Hsuan (1999) help to determine the modularization in the system. However, there are other factors that need to be considered besides the "interface constraint" and the "supplier buyer partnership". For example, a vital factor that needs to be covered is the functional analysis and functional decomposition for each module. Also for better understanding the interface constraint, the flows through the interfaces should be taken into account (Stone *et al.*, 2000).

2.10.4   Degree of Customization in an MC system

In this section we are regarding the extent of the customization factor in an MC system as the means not the ends. Customization is nothing but a tool used to induce a higher level of customer satisfaction and to concur a wider range of market niches. This tool may not necessarily achieve its goal for many reasons. Either it is excessively used, under used or improperly implemented. For example, an element of customization in a mass production system may attract more customers and increase sales revenue; while too much customization in a mass production system may lead to higher costs and diminishing increments in sales revenue. On the other hand, a company may have the right level of customization yet, because some of the MC principles are not properly implemented, the system does not achieve the desired goals. The aim of this section is to touch upon the literature for the degree of customization in an MC system.

Looking at an MC system from a logical perspective: what is the degree of customization? How is it different from standardized production or from a built to order system? A direct answer might precipitate in the number of variants that can be potentially generated or the degree of comfort or satisfaction offered to the customer. There has been some literature describing the degree of customization, however, none really agreed on a unified form of

measurement for that. Even though, the degree of customization in an MC system can be intuitively conceived, challenging to come up with generic scale. The reason is simple: each industry varies from the other, and a measurement of customization that works for one industry may prove invalid for another. Some components also contain continuously variable features that cannot be treated as discrete interchangeable components.

Some work involved forming a survey or questionnaire and asking a wide range of manufacturing companies their perception of how far they are customized, and the correlation between the degree of customization, business performance and information technology (Chung *et al.*, 2005). Similar work focused on Modularity-Based Manufacturing Practices (MBMP) and its correlation between customer closeness and MC capability (Tu *et al*., 2004). All this work found a somewhat positive correlation to their hypothesis. However, their main means of quantifying MC was through surveys asking the participants their own subjective perspective on their level of MC which can be vague. Other work tackled the degree of MC from a customer perspective. For example, Duray *et al.* (2000) and Piller (2006) referred to the degree of MC as the level of customer involvement in the production cycle.
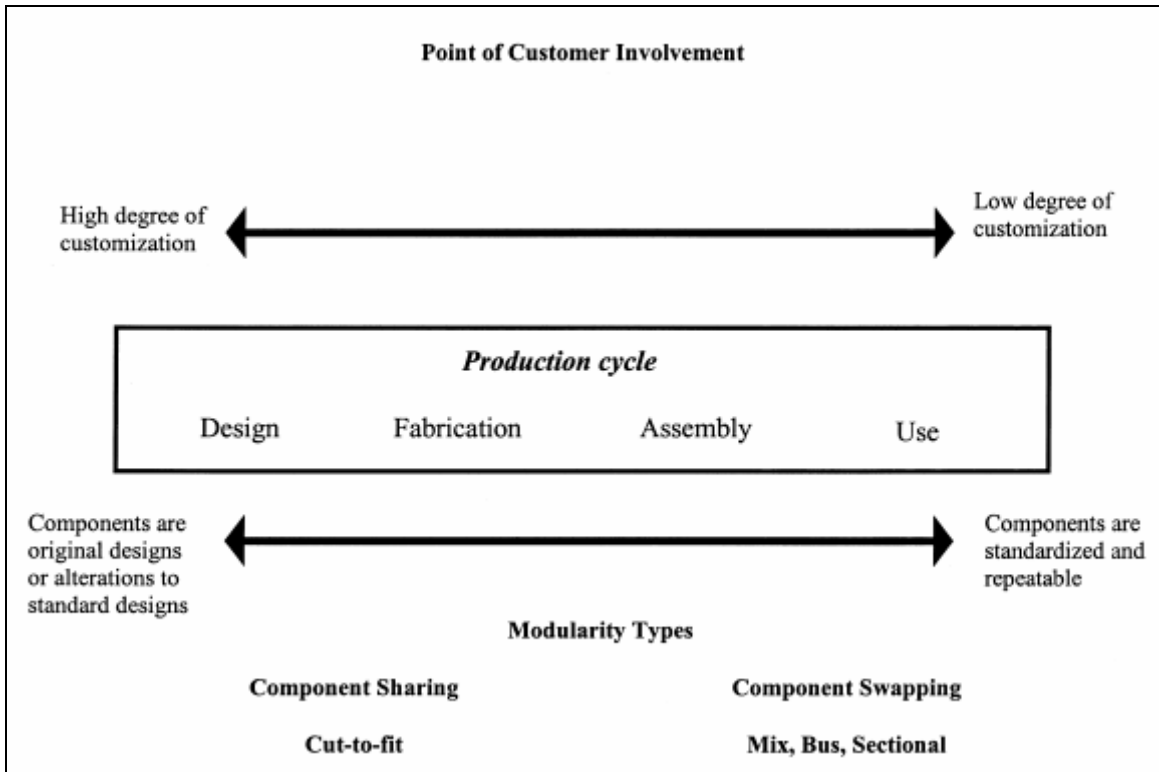
Figure 2.28 Customer involvement and modularity in the production cycle (obtained from Duray *et al.* (2000).

Other work involved mathematical models focused on modularity as reasonable unit of measurement. "Modularity bounds the degree of customization of the product and distinguishes mass customization from pure customized products" (Eggen, 2003). This area will be the starting point of this research in identifying quantification for the degree of customization in an MC system.

2.10.5   Granularity in a Mass Customization System

According to Du *et al.* (2000) in an MC system the products share two elements: First, the "common bases" which represent the standardization aspect of the product that allows for economies of scale. Second, the "differentiation enablers", facilitate variety generation and

represent the customization aspect of the product, and this promotes economies of scope. However, the dilemma here is what is the best ratio or level of "common bases" to "differentiation enablers" that would be most effective for an MC system designed for a specific industry. Increasing the level of differentiation enablers in a product would mean increasing the level of customization. Whereas increasing the "common bases" would raise the level of standardization. There is an evident tradeoff which is associated with lowering or raising the degree of customization in an MC system. This is sometimes referred to as the "granularity tradeoff "or the "level of granularity". (Tseng and Xuehong, 1998; Tseng and Jiao, 1996; Jiao, 1998). According to those authors, the appropriate levels of granularity are achieved by balancing the commonality and logistic costs which can be determined by the following:

- Current and future customer needs

- Communality in the design fulfillment

- Ease of configuration

- Appropriate level of aggregation

If aggregation is too low level, then the number of constructs becomes too high and the configuration is too hard to handle "nuts and bolt level". On the other hand, if the aggregation is too high level, then communality may be insufficient to generate significant variants. The highest level of aggregation would refer to a fully integral product that is not customizable. By controlling the level of modularity in a product a solution space for amount of potential variant generation can be determined, which in a way represents a means of measuring the degree of customization in an MC system.

2.11   <u>Product Variety Management and Postponement</u>

Production variety management includes several concepts that can be applied in MC environments but on a component level rather than on product level (Ho *et al.,* 2003). Such concepts involve component demand forecast, postponement, and other. One of the most significant concepts, that we shall discuss, is Postponement, which was first introduced by Alderson (1950). It means delaying of an event in an attempt to reduce the risk and uncertainty costs. There are three types of postponement that has been described by Bucklin (1965): Time, Place, and Form Postponement. Time postponement refers to delaying any procedures in a production or service environment until more specific information is received; such as, for example, delaying packaging until an order is received. Place postponement refers to storing products or spare parts in a common location until an order or more information is received. This scenario is typically applied as a pooling effect in a multi-echelon inventory system, where spare parts or semi-finished goods from different sources are grouped in a common distribution center awaiting for specific orders or destinations to be known. Form postponement refers Delayed Product Differentiation (DPD) which is related to products and production processes. The point of differentiation is "the stage after which the products assume their unique identities" (Lee *et al.*, 1997). Before that point all the common processes take place; after that products start to undergo special processes depending their unique features or parameters required. The aim is to delay this stage to reduce the uncertainty of adding a value to a product that may not be requested.
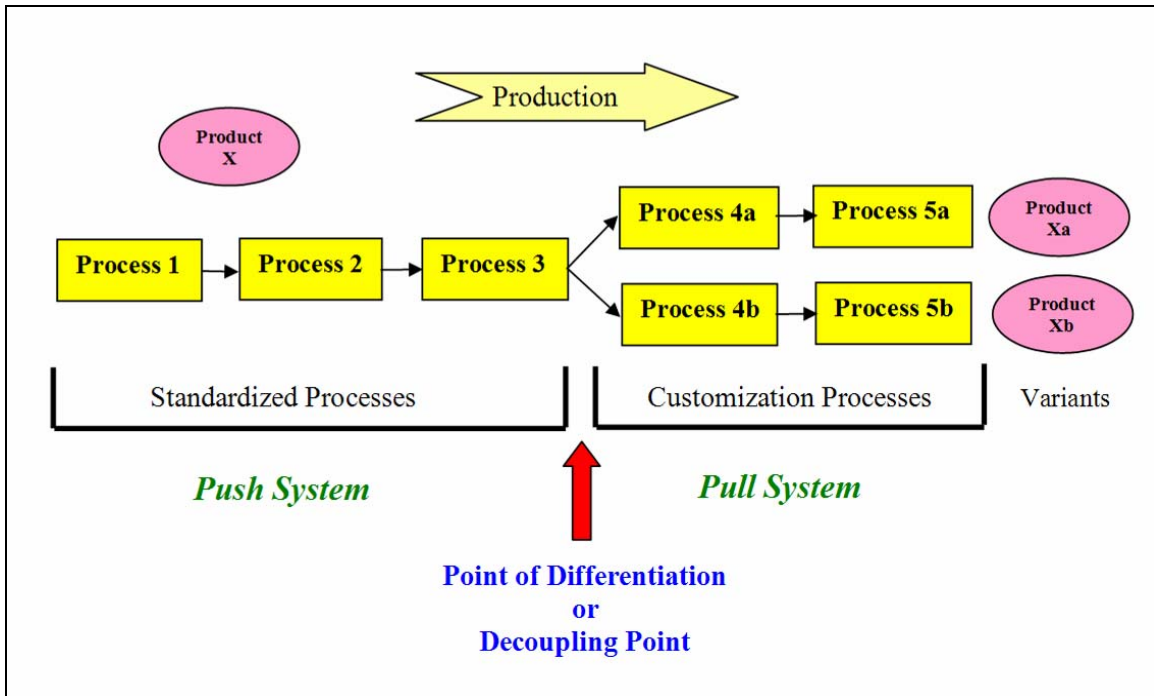
Figure 2.29 Point of Differentiation in Manufacturing System.

Applying a DPD system would involve moving the decoupling point further down the stream of a production line (Figure 2.29). According to Blecker (2005), this framework combines both the customization and standardization aspects of the production. The "degree of customization" decreases as the point of differentiation moves towards the end of the value chain and vice versa.

Delaying the decoupling point has several advantages which includes lowering the level of complexity such as the production planning, scheduling, quality control and others. However, by delaying the differentiation point, the degree or level of customization is also decreased giving less flexibility of choice for the customer. Blecker (2005) describes methods of quantifying the "Variety Induced Complexity" to assess the cost and benefits of applying DPD. Piller (2006) describes the decoupling point from a customer perspective, where the customer collaborates in the design or co-creates the product during the production phase. The decoupling

point in an MC system is the stage after which the customer involvement starts. Figure 2.30 shows that this point can be positioned at any location starting from the "Engineering" phase all the way to the "After sales". This point identifies an equilibrium position where the Manufacturing Productivity Forces and the Customer Flexibility Forces meet, which is referred to as the "Order de-coupling point" (Piller, 2006).
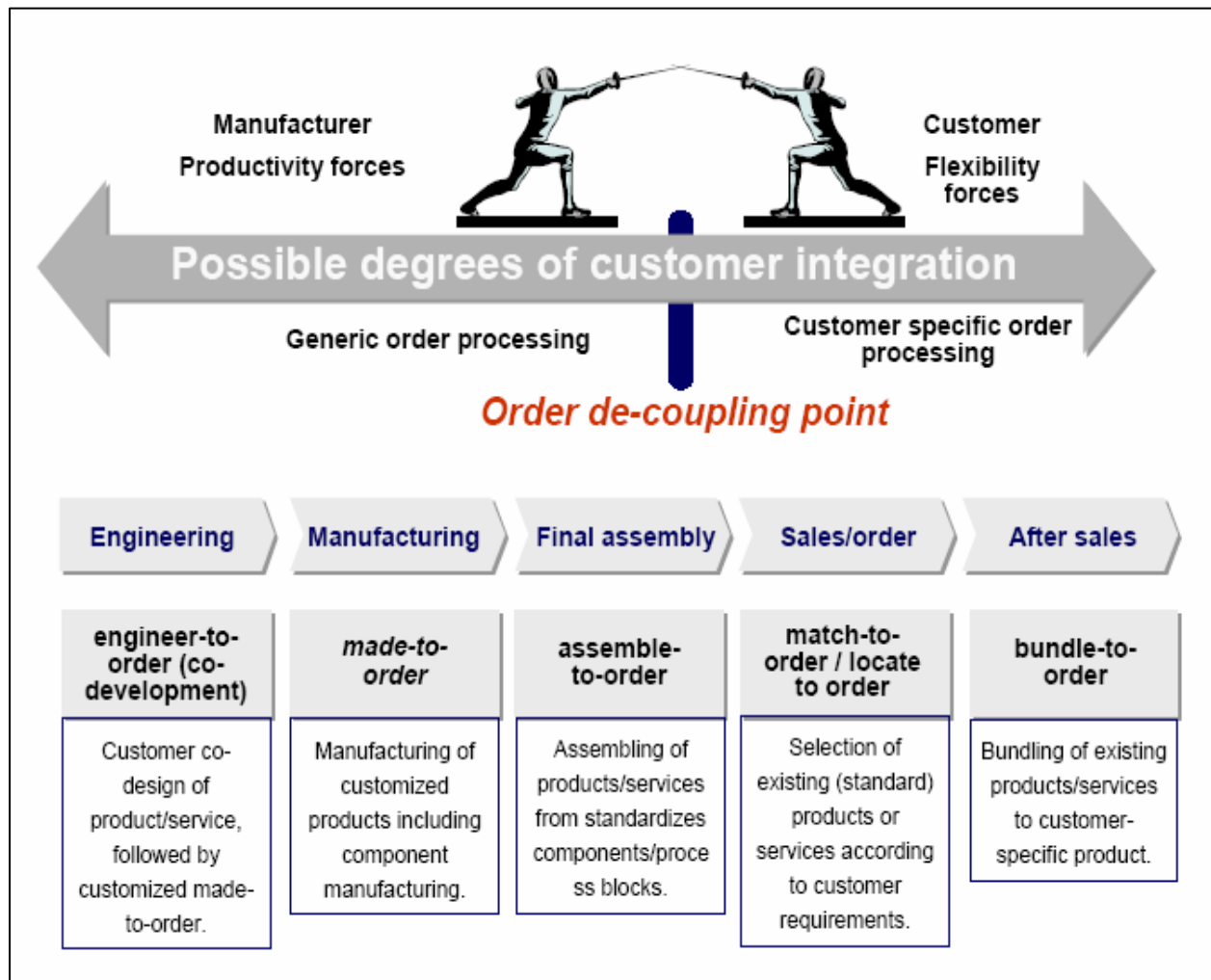
Figure 2.30 Order de-coupling point (obtained from Piller (2006)).

Lee *et al*. (1997) identified three approaches for implementing DPD that are widely used: "Standardization", "Modular design", and "Process Restructuring".

- *Standardization* refers to the use of common resources and processes. By having a standard element in production reduces the complexity of the system, partially captures economies of scale benefits, facilitates the handling of Work in Process WIP, and reduces uncertainty.

- *Modular design* refers to the functional decomposition of the product into modules and sub-modules that can be easily manipulated and assembled. This makes it easier to delay the assembly operation at a later stage when more information about the product becomes available.

- *Process Restructuring* refers to the re-sequencing of manufacturing processes in such a way that common operations take placed at an early stage, and the variation processes can be delayed at a later point when orders are being established.

According to Piller *et al.* (2004) there are savings involved in conducting the manufacturing and assembly process on an "on-demand" basis rather than "produce-to-stock" basis. Those savings can be reflected in various fields such as finished goods inventory (FGI) reduction, fashion risk reduction, Bullwhip Effect reduction and others.

2.12   Impact of the Information Technology on Mass Customization

Lately the digital technology has been progressing in an astonishing pace. Many interactions are now accomplished via the internet, such as: selling buy, banking, traveling, communicating, learning, entertainment, researching, and many others. That is due to the advances in speed and accessibility and reliability of the net, in addition to the overwhelming

progress in Customer Relationship Management (CRM) and other Information Technology (IT) tools. Many purchases that once needed geographical mobility and excessive bureaucratic procedures are now smoothly and quickly performed by the customer through the internet by means of highly user friendly interfaces. This has set an ideal environment for MC systems to thrive.

2.12.1   Role of Customer Relationship Management in MC Systems

The key issue is that the customer does not always know exactly what he/she wants or what will promote their utmost satisfaction. The customer can design a product and then after using it realizes that it is not the most suitable one; and another choice would have been better. If customers receive too much unguided flexibility or degrees of freedom while placing an order in a mass customization system, it can result to "mass confusion" (Huffman *et al.*, 1998; Piller, 2006). That is not surprising at all since the customer is not expected to be an expert in the field to know which mix of characteristics would best fit his/her needs. "… customers are not product experts and do not dispose of adequate product knowledge" (Blecker *et al.*, 2004). The customer cannot be condemned for a faulty or inadequate choice "it's your choice … it is not our problem if you do not like what you designed or selected yourself!". To avert this dilemma, while conserving the personalization aspect, a CRM system can offer a user friendly interface with useful guidance to help the customer make a more appropriate selection of attributes based on an expert system.

With the help of the current information technology, many businesses and firms engaged into the "one-to-one marketing - also called as the CRM band wagon to better understand

customer needs, to improve interaction with their customers, and to create higher customer value

(Tu *et al.*, 2004)

In a study conducted by Blecker *et al.* (2004) where the distinction was made between the subjective and objective needs of the customer, as seen in Figure 2.31 The subjective needs represent explicitly articulated requirements of the customer, which may not necessarily lead to his/her optimal satisfaction. Whereas the objective needs are the implicit needs that the customer may not explicitly require or know about, but will hold the utmost value-added and optimal satisfaction (Blecker *et al.*, 2004).
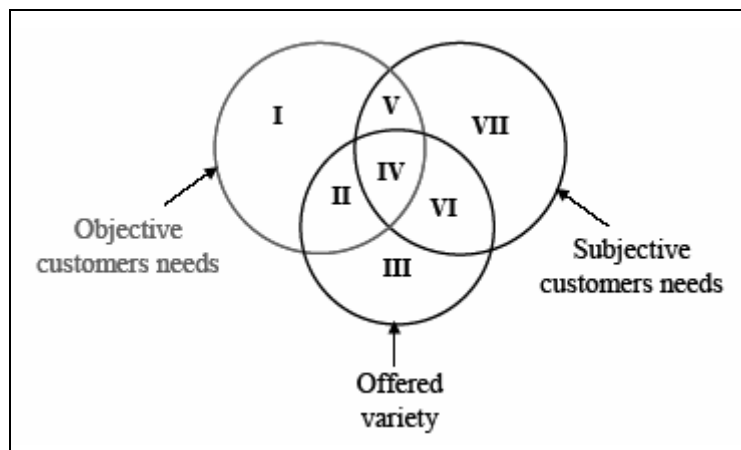
Figure 2.31 Discrepancies existing between the objective and subjective customers' needs
(obtained from Blecker *et al.* (2004)).

The aim of this study is to find a way of reducing the gap between the subjective and objective needs or increasing the region (V + IV), while providing the variants that will mostly fulfill those requirements, which is represented by region (IV). Actually, nobody is interested in variants that will never be needed or selected, that could be achieved by reducing region (III). The best case scenario would be to have region (IV) as the dominant surface area in the Venn diagram. To do that there has to be a very close coordination between the customer and the MC

system. The manufactures needs to thoroughly understand the psychology and precise needs of the customer to push variants in the regions where the customers objective or subjective needs will most likely be. On the other hand, well sophisticated CRM systems will help the customers make better decisions, or understand more deeply their own needs. In a study, looking upon MC from a customer perspective, evidence was found of a direct correlation between the Customer Closeness (CC) and the MC capability (Vonderembse, 2004).

2.12.2 Economies of Integration

Piller *et al.* (2004) coined the term "Economies of integration", which refers to saving potentials resulting from integrating the customer into the production process. Piller *et al.* (2004) identified three main areas for cost saving potentials: First, postponement where some activities can be delayed until a customer order is made. This reduces the risk of producing to stock or ending up with a surplus of FGI (Finished Goods Inventory). Second, more precise "first hand" customer information is availed which is referred to as "Sticky information" (von Hippel, 1994). Having access to first hand customer information is very valuable in terms of market research and product development. Third, is the increase of customer loyalty and "re-use" due to the direct interaction with customer or customer experience. Establishing a strong and stable relationship with the customer reduces marketing efforts and costs. Without proper and well sophisticated information system there is no chance of establishing effective customer integration. The information system will help track the customer's orders and translate them to complex processing orders. In an MC environment, where there is a large volume of orders, high speed information systems accompanied by well established data bases are imperative for an effectiveness of the integration process.

2.12.3 The Long Tail

"Selling less of more or selling more of less" was a dilemma that was analyzed by Anderson (2006) when he wrote his book "The Long Tail". The idea of the long tail is that if range of products is offered in the market, typically only a few items or a small percentage will become very popular "Top Hits" and will experience high sales. On the other hand, the remaining will seldom be purchased only by remote customers. The traditional producers or salesmen tend to truncate the curve near the head, which is represented by the yellow region in Figure 2.32 to capture the most popular sales. According to Anderson (2006) there is a significant portion of the market niches that lies in the "tail", which is represented by the blue and white region. The current advances in technology such as IT and internet capabilities enables companies to target a wider portion of the "tail", while keeping costs at a minimum. The author presented an example of two record companies one that conducted their sales online and offered a much wider variety of songs than a traditional record store that had a limited number CDs on the shelves. The online record company was able to capture both: the market for the "top hits" and the market for the unpopular songs that included records that may be only ordered once.
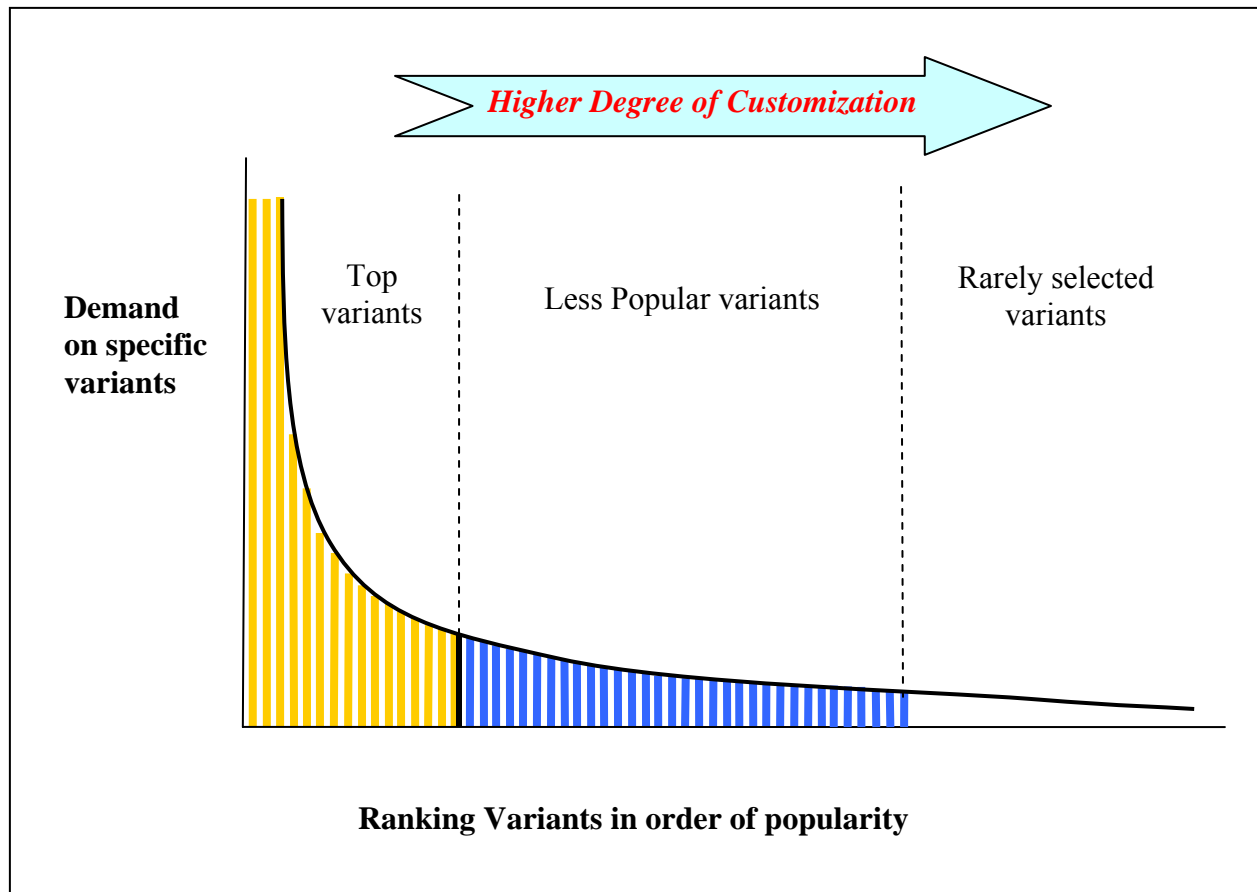
Figure 2.32 An analogy between the Long Tail and the degree of customization in an MC system (obtained from Anderson (2006)).

Adopting from Anderson's concept an analogy was made for an MC system, where the degree of customization would be the potential number of variants that can be availed upon demand by using the mix and match concept. Similar to the "Long Tail" model, a certain range of variants (or combination of modules forming products) will be more popular. While, on the other hand, the largest portion of potential combinations will be rarely or never ordered. The tricky part is that the manufacturer or producer does not usually know which set of combinations will be most popular. Therefore, the wider the range of variants that can be potentially generated the better the chances of capturing the future popular items, while serving a larger number of remote or unique customers that may request rarely selected variants. The higher the degree of

customization the higher the scope of variants that can be generated and in turn the larger the portion of the tail captured. The aim of this research is to find an optimal point that will truncate the tail as far as possible towards the tail, while keeping the manufacturing costs at a reasonable level.

2.13   Research Summary

Throughout the literature review, there were several points that were focused upon that are considered as important background areas for this research. A list of basic sources that covered those areas is sorted in Tables: 4, 5 and 6. The check mark indicates which articles or sources mainly contributed in each areas or subjects.

The following is the description of the points or areas that are listed in Tables 4, 5 and 6:

- Definitions of MC: Those journal articles or sources contained definitions for MC from different authors' perspectives.

- DFMC: Those sources include material on the design of an MC system during the product development phase.

- Product Architecture: Those sources discuss in depth the product architecture in terms of family based designs.

- Modularity: Those sources covered in depth an understanding of modular production or modular design, and the benefits of using modular systems versus integral ones. Also methods of determine or designing appropriate modules are covered.

- Heuristic for module identification: Those sources included heuristics that were developed to identify appropriate modules within highly complex systems.

- Granularity: Those sources touch upon the concept of granularity and its effect on modular production.

- Degree of MC: Those include sources that discuss the degree of customization different perspectives. Some authors view the degree of customization from a modular or variant generation prespective, others view it from the degree of customer integration and the earliness of co-design process.

- MC Capability: Those sources reflect upon the ability of a firm to establish an MC system and the extent of IFMC (Infrastructure for Mass Customization). Modularization is also an indicator of MC Capability as it determines the ability of a firm or manufacturing system to become modular.

- DPD (Delayed Product Differentiation): Those sources discuss in detail the concept of DPD, postponement or the decoupling point, the ability to implement such systems and their benefits to an MC system.

- Flexible Manufacturing: Those sources discuss the impact of Flexible Manufacturing on an MC system.

- CRM (Customer Relationship Management): Those sources tackle the importance of advanced information technology and in particular CRM systems as a main factor to the success of an MC system.

- Marketing for MC: Those articles discuss MC systems from the customer view point and stress the marketing strategies that strengthen the customer-producer relationship strategies.

- MC throughout the Supply Chain: Some sources state that to have a successful MC system, the IFMC should extend beyond the boundaries of the manufacturing plant or

production system. The suppliers should be educated and equipped to handle the new
system. Other sources suggest the implementation of MC throughout the supply chain by
adopting the concept of Virtual Enterprise.

Table 2.4 List of sources that covered the main background areas for this research.

Author	Year	Article Title	Definitions of MC	DFMC	Product Architecture	Modularity	Heuristic for module identification	Granularity	Degree of MC	MC Capability	DPD	Flexible Manufacturing	CRM	Marketing for MC	MC through the Supply Chain
Arnheiter et al	2004	A typology to unleash the potential of modularity	√			√									
Baker et al	1999	AGENTS AND THE INTERNET:Infrastructure for Mass Customization	√										√	√	√
Baldwin et al	1998	Managing in an age of modularity				√									
Bardakci et al	2003	Mass-customization in marketing: the consumer perspective	√											√	
Beaty	1996	Mass Customization	√	√					√	√					
Berry et al	1997	Manufacturing flexibility methods for measuring the impact of product variety on performance in process industries							√		√				
Blecker et al	2005	Modularity and Delayed Product Differentiation in Assemble-to-order Systems: Analysis and Extensions from a Complexity Perspective							√		√				
Blecker et al	2004	An Advisory System for Customers' Objective Needs Elicitation in Mass Customization			√										
Chung et al	2005	An Empirical Study of the Relationships Between IT Infrastruacture Flexibility, Mass Customization and Business Performance			√	√							√		
Corbett	2005	Mass Customization versus Mass Production: Variety and Price Competition			√										
Corbett et al	2003	A configuration design based method for platform commonization for product families			√	√									
Cullinane et al	1997	A Generic IDEF0 Model of a Production System for Mass Customization	√			√									
Du et al	2000	ARCHITECTURE OF PRODUCT FAMILY FOR MASS CUSTOMIZATION		√											
Du et al	2002	Identifying customer need patterns for customization and personalization	√	√									√	√	√
Duray	2002	Mass customization origins: mass or custom manufacturing?	√										√	√	
Duray et al	2000	Approaches to mass customization: configurations and empirical validation				√		√		√					
Eggen (1)	2003	Modular Product Development				√	√								
Eggen (2)	2003	When is modularization appropriate?				√	√								
Fiore et al	2004	Individual differences motivations, and willingness to use a mass customization option for fashion products	√										√	√	
Fiore et al	2001	Relationships between optimum stimulation level and willingness to use mass customisation options	√								√				√
Fujita	2002	Product Variety Optimizatoin Under Modular Architecture				√			√						

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Author	Year	Article Title	Definitions of MC	DFMC	Product Architecture	Modularity	Heuristic for module identification	Granularity	Degree of MC	MC Capability	DPD	Flexible Manufacturing	CRM	Marketing for MC	MC through the Supply Chain
Fujita et al	1999	Product variety deployment and its optimization under modular architecture and module commonalization			√	√			√						
Garud et al	1994	TECHNOLOGICAL AND ORGANIZATIONAL DESIGNS FOR REALIZING ECONOMIES OF SUBSTITUTION				√			√				√		
Glimore and Pin	1997	The Four Faces of Mass Customization	√										√	√	√
Hai-juri et al	2003	Process Analysis in the generation of Product Modularization Based on Fuzzy Cluster				√									
Hoek et al	2000	The Role of Third-Party Logistics Provides in Mass Customiztion	√												√
Hsuan	1999	Modularization in New Product Development: A Mathematical Modeling Approach	√			√			√	√					√
Hu et al	2005	Study on the Architecture of Product Collaborative Design System in Mass Customization Base on J2EE	√		√										
HUANG et al	2004	Special Issue: Platform product development for mass customization	√	√	√										
Jiang et al	2003	Research and development on constraint-based product family design and assembly simulation		√	√										
Jiao	1998	Design for Mass Customization by Devloping Producut Family Architecture	√	√	√	√	√	√				√	√		
Jiao et al	1999	A methodology of developing product family architecture for mass customization	√	√	√										
Jiao et al	2000	Fundamentals of product family architecture	√	√	√										
Jiao et al	2002	Towards high value-added products and services - Mass Customization and beyond	√	√									√	√	√
Jiao et al	1998	Virtual Prototyping for Customized Product Development	√												
Kakati et al	2002	Mass customization – needs to go beyond technology			√				√			√			
Lampel et al	1996	Customizing Customization							√				√		
Lee et al	1997	Modelling the Costs and Benefits of Delayed product Differentiation				√			√		√			√	
Magill	1996	Customising bicycles through the integration of best practices	√												
Martin et al	2002	Design for variety: developing standardized and modularized product platform architectures				√							√		
Mena et al	2000	Supply Chains for Mass Customization	√										√	√	√
Pilkington et al	2000	MASS CUSTOMIZATION: CONFLICTING DEFINITIONS	√										√	√	√
Piller	2006	Mass Customization Success factors and challenges to co-create value with your customers	√						√		√		√	√	
Piller et al	2002	Mass Customization: Four approaches to deliver customized products and services with mass production efficiency	√										√	√	√
Piller et al	2004	Does mass customization pay? An economic approach to evaluate customer integration							√		√				

Author	Year	Article Title	Definitions of MC	DFMC	Product Architecture	Modularity	Heuristic for module identification	Granularity	Degree of MC	MC Capability	DPD	Flexible Manufacturing	CRM	Marketing for MC	MC through the Supply Chain
Qiao et al	2004	Process Control and Logistics Management for Mass Customization Manufacturing										√			
Qiao et al	2003	Flexible Manufacturing System for Mass Customization Manufacturing			√	√						√			
Qiao et al	2002	Simulation System Modeling for Mass Customization Manufacturing				√						√			
Schilling	2000	Toward a General Modular Systems Theory and its Application to Interfirm Production Modularity				√									
Siddique et al	2003	A mass customization information framework for integration of customer in the configuration/design of a customized product				√							√	√	
SIMPSON	2003	Product platform design and customization - Status and promise	√		√										
Stone	2000	A HEURISTIC METHOD FOR IDENTIFYING MODULES FOR PRODUCT ARCHITECTURES				√	√								
Tseng and Jiao	1998	Concurrent Design for Mass Customization		√											
Tseng et al	1996	Design for Mass Customization	√	√											
Tseng et al	1997	CASE-BASED EVOLUTIONARY DESIGN FOR MASS CUSTOMIZATION	√		√			√	√					√	√
Tseng et al	1998	Design by customers for mass customization products	√	√	√			√							
Tu et al	2001	The impact of time-based manufacturing practices on mass customization and value to customer	√							√					
Tu et al	2004	Measuring Modularity-Based Manufacturing Practices and Their Impact on Mass Customization Capability: A Customer Driven Prespective				√								√	√
Ulrich	1995	The role of product architecture in the manufacturing firm												√	√
Wu et al	2004	Manufacturing Process Reengineering for Mass Customization by Using Flexibility Analysis	√									√			
Xiao et al	2003	Research about Design Platform for Mass Customization Based on Library of Customization Resource	√		√										
Xiuxu et al	2003	A www-based customer-driven product design and manufacturing solution for Mass Customisation	√										√	√	
Xuanfang et al	2002	Knowledge Modeling in Design Process Knowledge Modeling in Product Family Design for Mass Customization	√	√	√										

2.14   Research Gap

The aim of this research is to have a better understanding for the degree of customization in an MC system and defining a model that would help determining an optimal or near to optimal degree of customization, based on strategic management goals and resource constraints. Since each industry varies from the other it is challenging to find a generic model for the degree of customization that would capture various industries. Each industry or organization that is willing

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to venture in MC has a unique nature, set of requirements and goals. Therefore, there is a need for the model to be flexible to adapt to different types of industries.

There are various areas of research that contributed to an understanding of the degree of customization in an MC system. Each source addresses the level of customization from a slightly different angle depending on the area of research involved. Table 2.7 lists some of those sources with their corresponding view of the degree of customization in an MC system.

Table 2.5 List of article that contributed to the degree of customization concept.

Author	Year	Degree of Customization for each source
Fujita	2002	This article focused on the degree of customization by optimizing product variety during a product development stage in concurrency with other aspects of Design for X (DFX).
Fujita et al	1999	This article focused on the degree of customization by optimizing the module selection, by defining the communality during the product architecture.
Hsuan	1999	This article touched upon the degree of customization by defining the modularization aspect involved in a product, which is the ability to form modules. This was done by formulating a model that includes the number of components and interface constraint.
Berry et al	1997	This article focused on the degree of customization by analyzing the effect of generating product variety on the market and the corresponding price sensitivity.
Lampel et al	1996	This article focused on the degree of customization by analyzing the standardization versus customization components in the industry.
Blecker et al	2005	This article focused on the degree of customization from a DPD (Delayed Production Differentiation) perspective. The degree of customization decreases as the decoupling point goes further down the stream (towards the end of the production line)
Lee et al	1997	This article focused on the degree of customization from a Postponement perspective; throughout the supply chain.
Kakati et al	2002	This article focused on the degree of customization by analyzing the technological aspects that can induce a higher degree of customization.
Piller et al	2004	This article focused on the degree of customization by examining the degree of customer integration into the process. That is achieved by analyzing how early the co-creation (between the customer and producer) occurs during the production process.
Piller	2006	This article focused on the degree of customization also by examining the degree of customer integration and involvement in the production process.

All the above sources refer to the same concept and share a common understanding of MC. Many authors recognize the tradeoffs between the costs and benefits of implementing an MC system. The literature refers to MC as a system that consists of a standard and customizable component, which are sometime referred to as the "common bases" and "differentiation enablers" (Du *et al.*, 2000). Typically, increasing the level of customization in an MC system would waive a portion of standardization. Most of the literature views the degree of customization as how early or how far the customer is integrated in the production cycle which is

defined as the order decoupling point. In this study we are addressing the degree of customization from a product structural perspective.

To the best of our knowledge, none of the literature covers the concept of linking the tradeoffs involved in an MC to the degree of customization in an analytical form. Therefore, the aim of this research is to introduce a "Customization Scale" that will provide a measure or indicator to the level of customization for a product in an MC system; then determine the best level of customization at which a company should operate, based on the company's predefined goals and resource limitations.

CHAPTER 3: METHODOLOGY

3.1   Overview of the Chapter

This chapter is divided into three sections. The first section presents the general theory, which involves an understanding of the degree of customization for a product and its effect on the profitability curve. Also, a general hypothesis is made regarding the behavior of the profitability in an MC system which includes process improvement or introduction of technology advances. The second section presents a technique by which a specific and quantifiable measure for the degree of customization can be achieved. In this research, we introduce the term "Magnitude of Customization" (MOC) as a unit to measurement the degree of customization on a customization scale (CS). The MOC is based on quantifying the extent of options per modules or the extent of customizable features per component for a product in an MC system. The third section suggests a suitable multi-criteria analysis technique that will thoroughly consider the tradeoffs between the benefits and costs associated with implementing MC at a specific customization level. This model should help determine the degree of customization that would best fulfill the strategic goals of the organization at a given technological capability and resource constraints.

Before describing the methodology details, a set of assumptions are made that will follow throughout this chapter and the case study presented in Chapter 4.

1- We assume that the companies or organizations being analyzed only produce a single product family. For instance, if we are addressing Nike^{TM}, only the effect of a single category of products, such as tennis shoes, on MC is considered. Actually Nike is produces many different types of products besides sports shoes, such as t-shirts, swimsuits, and others. Since most companies are involved in the production of multiple product families, suggestions are made in Chapter 5 to expand the model to encompass more than one category of products in a single model.

2- In our model, we assume a pure Pull system; that is there is no need for demand forecast considerations. In the practical world, there is no pure Pull system; it is typically a combination of both Push and Pull. MC systems tend to have a more Pull than Push.

3- We assume that increasing the level of customization will help satisfy wider market niches, and hence, will have a positive effect on demand and sales.

4- In many cases, for MC systems that have an inadequate customer interface, increasing customization will contribute to customers' confusion rather than convenience. We assume that the MC systems being analyzed have a user-friendly customer interface, and that providing more options or flexibility will only add to value to the customer.

5- In our methodology, we assume Customization and Standardization to have an inverse relation; that is increasing the level of customization would imply less standardization and vice versa.

6- For simplicity, we assume that the organizational goals are independent, and that there is no significant correlation between them. In some cases, there may be some dependency or interaction between goals which, if taken into account, would yield more accurate results.

3.2   Profitability as a Function of the Degree of Customization

This section describes our theoretical view of the profitability of a firm in an MC system as a function of the degree of customization. Profitability here refers to the difference between the marginal benefits or extra gains due to customization (Table 3.1) and the additional costs incurred by venturing into MC (Table 3.2). We also show how technological advances and changes in the volume of production are expected to affect the profitability of the system.

Table 3.1 List of some important benefits or value-added gained by venturing into MC.

Benefits	Description
Premium Price	The additional price a consumer is willing to pay for a personalized product, or customization service.
Additional Market Niches	Additional market niches that can be captured due to a better fitting product or service that a standard product alternative would not have achieved.
Reduces FGI	In an MC system products are typically built on demand and not to stock, which reduces the storage costs and space requirements associated with Finished Goods Inventory (FGI).
Reduced Need for Demand Forecast	Customized products are built after an order has been received. That reduces the need for demand forecast.
Reduced Risk of Fashion Obsolescence	Customers control the shape, color, and most of the features pertaining to a product. There is less risk of customers disliking their design.
Reduced Product Returns	Customers dictate their exact needs and requirements. There is a less chance of product returning due to a misfit of need.
Reduced Product Liability Risk	By co-designing a product the customer shares part of the liability.
Reduced Loss of Reputation	By co-designing a product the customer shares responsibility of the product outcome especially the set of requirement that he/she placed.
Better First-hand Customer Information	First-hand customer information, also refers to as "Sticky information", is a valuable asset for market research (von Hippel, 1994).
Customer Loyalty and Re-use	Customers used to fulfilling their exact needs are less likely to revert to standard alternatives.

Table 3.2 List of basic costs or infrastructure investments that are experienced in MC.

Costs and Infrastructural investments	Description
Increased Level of Inventory	Higher level of customization or product variation induces a larger size of component inventory, procurement inconveniences and longer throughput time (cycle time).
Higher Cost/time of Assembly	Higher level of product differentiation results to high assembly costs than standardized alternatives.
Higher Cost of Scheduling	Higher product variety results to higher costs of scheduling, sequencing and handling. It is referred to as "Variety Induced Complexity" (Blecker, 2005).
Infrastructure for a Suitable MIS	Additional infrastructural investment costs are typically necessary to establish more suitable management information systems (MIS).
Management and Staff Training	Additional training costs are typically necessary to better prepare the staff and management.
Creating a CRM System for Customer Interface	Additional infrastructural investment costs are typically necessary to establish a specialized CRM system that guides customers in their product design and component selection process.
Changing Marketing Strategies	Other additional marketing investment costs to better address the customer from a customization standpoint.
Increased Cost of Quality Control	Process control and product or component inspection is more challenging when dealing with unique designs or assemblies. More advanced tools and strategies are typically required to handle that.
Risk of Failure	MC, being a newly applied concept, involves several unknown failure modes that the producer would not detect before the implementation of the system. This augments the risk of failure.
Brand Dilution	The worth of the brand may be in its appreciated mix of material and design. Giving the customer the freedom of altering the ingredients of the brand may dilute its value.

3.2.1 Profitability as a Function of the Degree of Customization

A Customization Scale (CS) has been introduced that shows the degree of customization as having an inverse relationship to the degree of standardization. This is based on the assumption

that, as we increase the level of customization or selection options for the customer, we are also waiving opportunities to standardize. The CS is represented as a value (or percentage) between 0 and 1, where 0 refers to pure standardization and 1 to full customization from a relative standpoint. A higher level of customization would typically encompass a larger number of product variants (product family), more optional modules to select from and have an early order decoupling point. On the other hand, a low level of customization (or high level of product standardization) holds a smaller number of product variants, less module options and the order decoupling point is closer to the final product. The product is composed of a few standard modules that include multiple functional and structural properties.
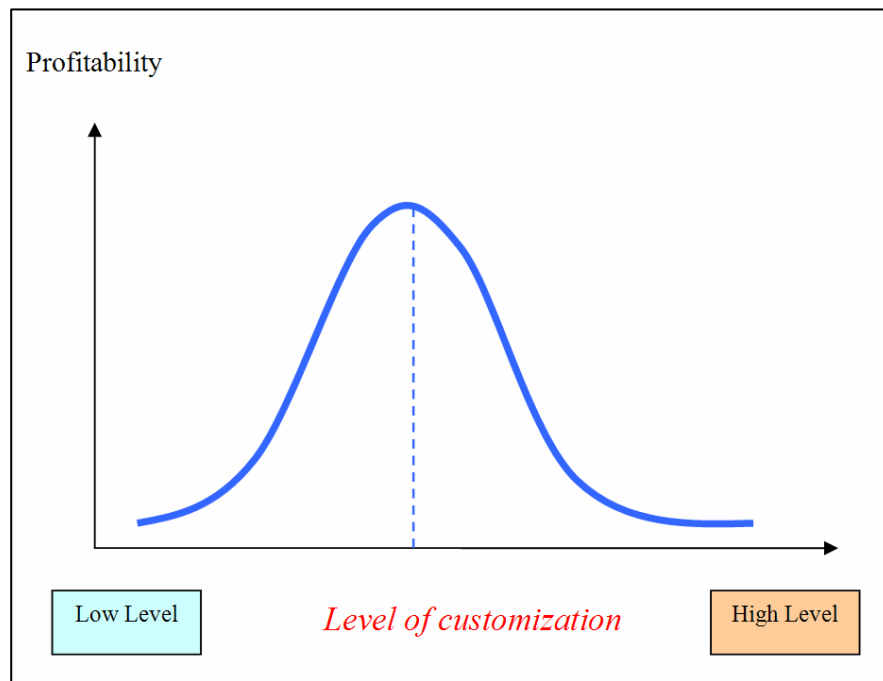
Figure 3.1 The profitability curve as a function of the degree of customization, for a particular industry.

As illustrated in Figure 3.1, an increase in the level of customization for a particular product infers giving up a portion of standardization. On the other hand, standardizing a process would naturally lead to losing a potential for customization. The profitability curve indicates the

level of additional profit realized by implementing MC at a given degree of customization and volume of production. The diagram represents the expected behavior of profitability as a function of the degree of customization. That is increasing the level of customization in a company would augment the customer benefits and company gains up to a certain level. Eventually, the investment and running costs will catch up and reduce the overall net benefits or profitability.

This level of customization varies from one industry to another and this depends, to a large extent, on the nature of industry, its products, and the market. The decision of "how much customization?" warrants classifying industries by type and identifying the influencing criteria that has to be considered in determining the level of customization. Hence, our target is to develop a model that is capable of categorizing various industries based on a known set of input parameters or indicators and determine influencing criteria and set targets for each that can be achieved through customization. The model should also consider any limitations or constraints in the product customization. Solving the model will require the determination of the potential contribution, due to customization, to every goal identified.

Figure 3.1 is a general representation of profitability versus the level of customization aiming to show the possible existence of a specific degree of customization that is most profitable for a particular industry. A more realistic profitability curve is expected to have more than one peak as shown in Figure 3.2.
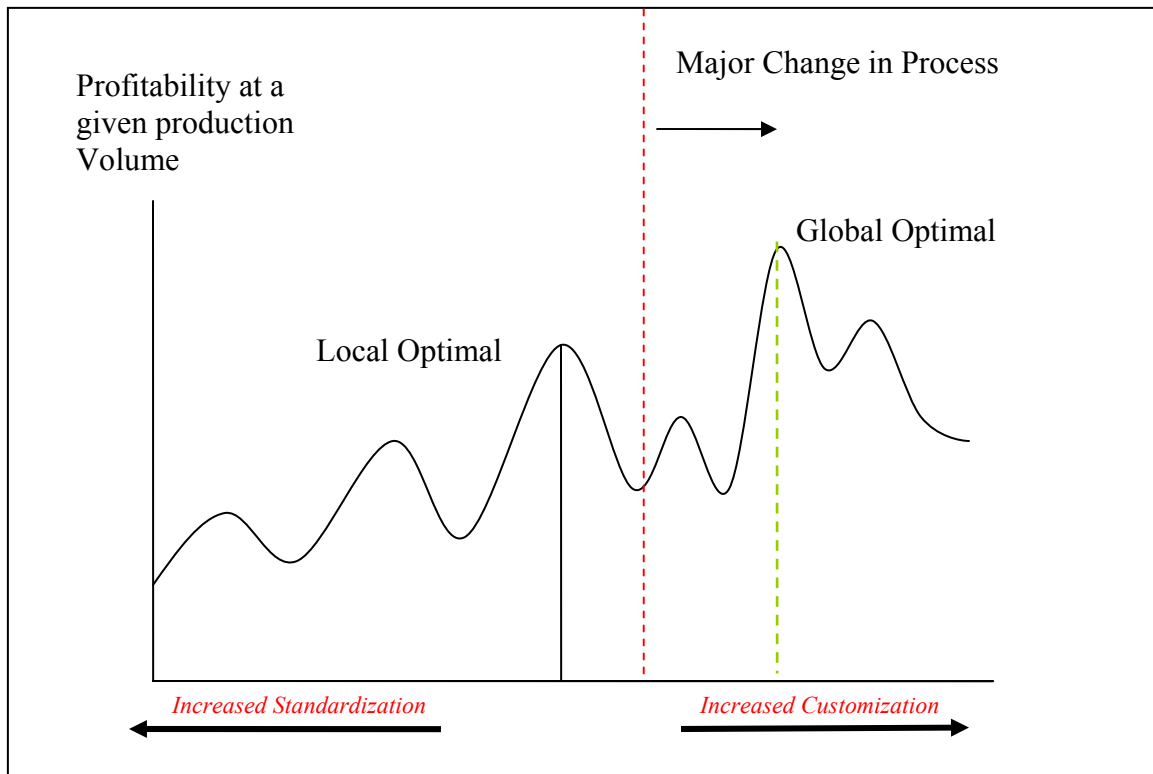
Figure 3.2 Local and Global Optima for the profitability curve.

There may be several local optima and a global optimum. Mass customizers would typically aim at identifying the global optimum, or achievable local optimum given the resource limitation and available technological capabilities. For an industry to move from one level of customization to the next, to capture the next peak, a major change in process is sometimes required. Increasing the level of customization without any process changes might only result in higher cost.

3.2.2   The Effect of Mass Customization Advances on the Profitability Curve

The introduction of technological advances and modern industrial concepts will make it easier for companies to customize more at lower costs. That will, in turn, change the characteristics of the profitability curve. For example, introducing the rapid manufacturing

technology will enable the producer to fabricate solid freeform parts at a cost that is independent of the geometrical complexity. Figure 3.3 shows that the profitability curve is expected to shift towards the "High Level" of customization end and achieve higher profitability upon the application of MC concepts. This shift reflects the fact that technological advances and the use of new production processes can render higher profitability to a firm while operating at a higher degree of customization.
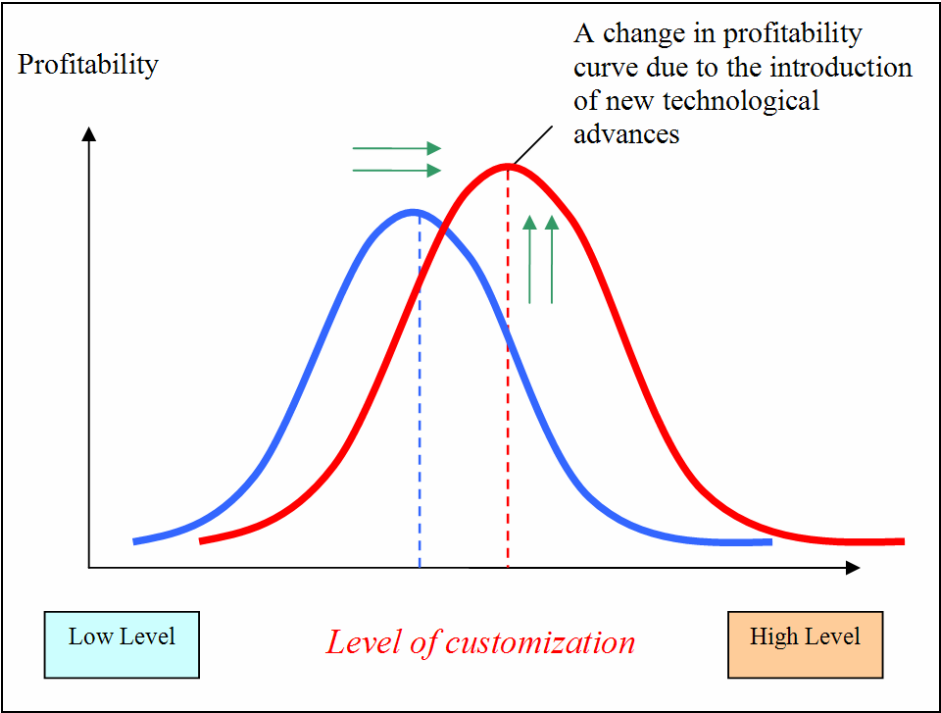
Figure 3.3 A shift in the profitability curve due to the introduction of new technologies and new processes.

3.2.3 The Combined Effect of Mass Customization and Production Volume on Profitability

MC has originally emerged to equip companies with a low to medium volume of production when competing with large companies that are experiencing the full benefits of economies of scale. That is the case during Japan's post-war expansion, where small to medium

sized companies needed to develop a new competitive edge when confronting giant mass

producing monopolies (Westbrook *et al.*, 1993). Typically, MC assumes a low to medium

volume of production. Customization at a high volume of production may entail higher

production costs. While, on the other hand, standardizing at low volume is in most cases

unprofitable. The response surface in Figure 3.4 shows the effect of altering the degree of

customization at various production volumes on profitability. The shape of the surface and the

location of the optimum depend on the nature of the industry and the technological capabilities

available.
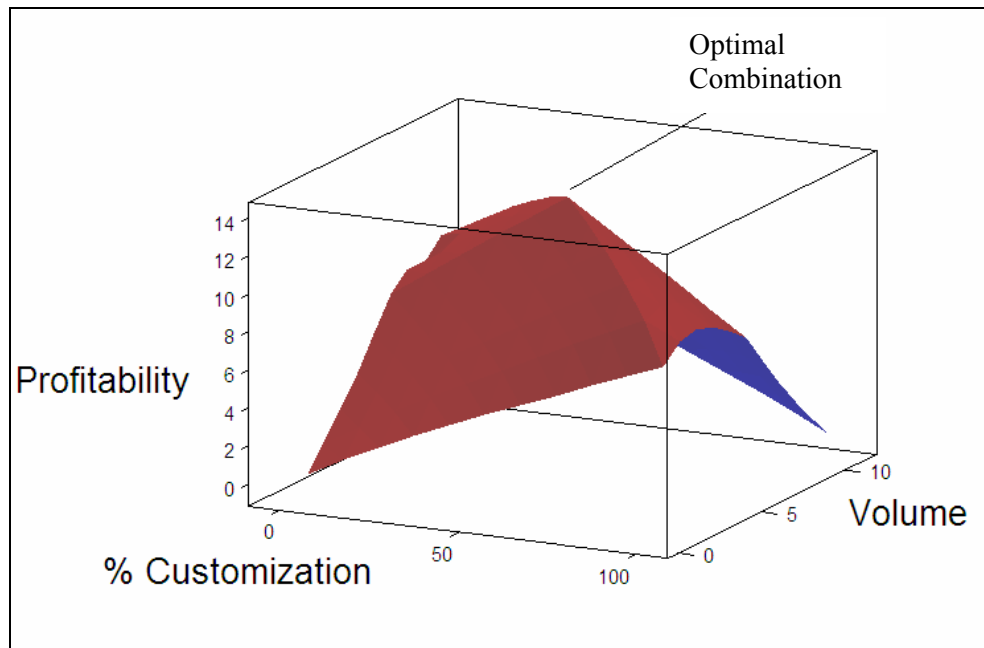
Figure 3.4 Profitability as a function of level of customization and volume of production.
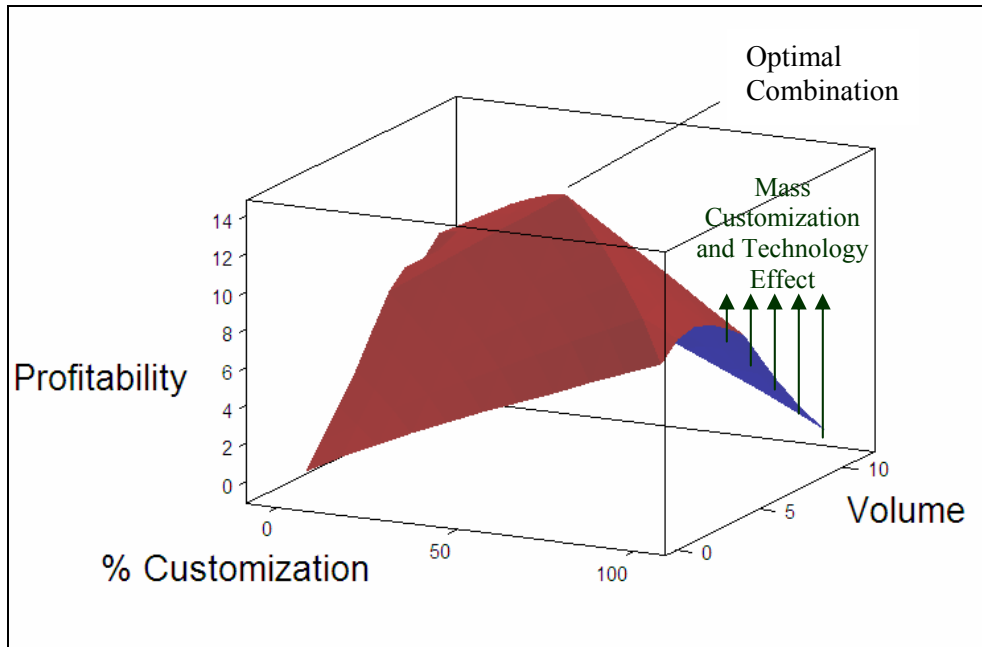
Figure 3.5 A change in profitability patterns based on the introduction of a new technology.

The introduction of MC advances is expected to greatly affect the pattern of the profitability surface. The role of new technology is to sustain or increase the benefits of MC at higher volumes of production. The arrows shown in Figure 3.5 indicate the manner by which the profitability surface is expected to change based on technology advances such as, for example, Rapid Manufacturing or a newer and more capable IT system.
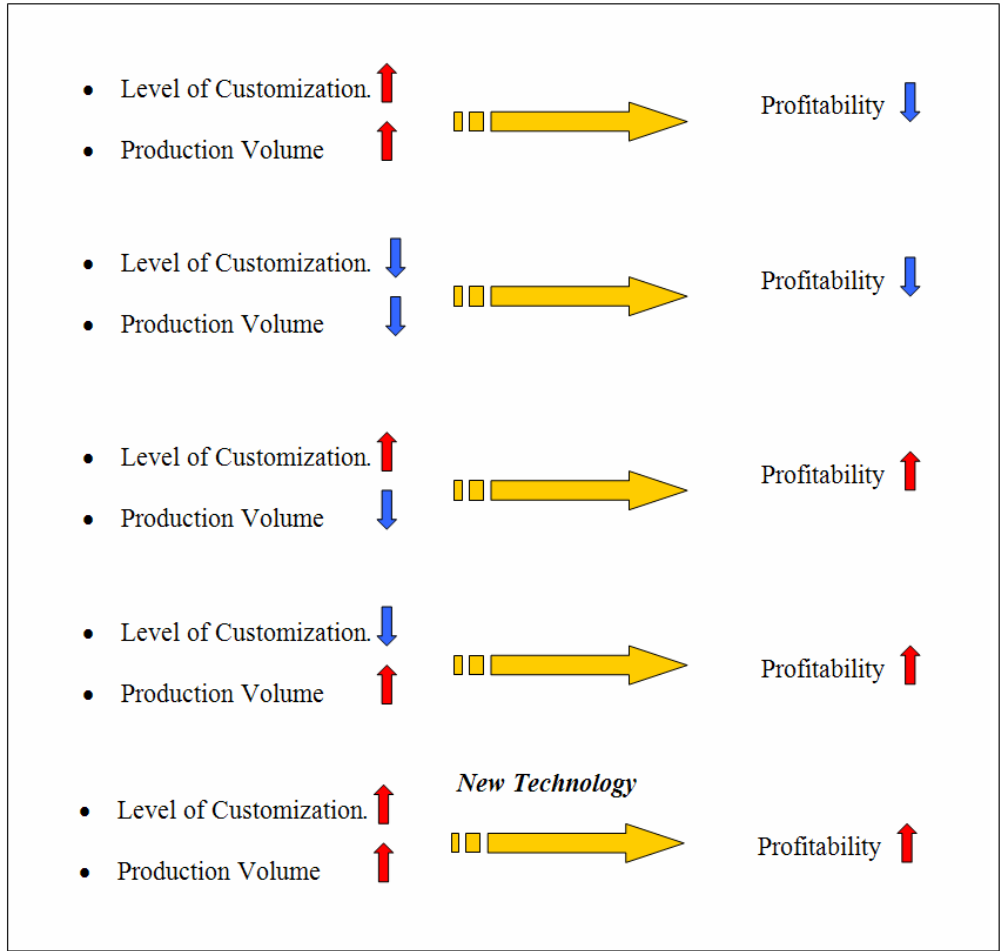
Figure 3.6 The effect of a new technological advance on the optimal level of customization.

3.3   Measuring the Degree of Customization for a Product

In this section, a technique for quantifying the degree of customization for a product in an MC system is demonstrated. Section 3.3.1 discusses how the product modular structure is formed. In Section 3.3.2, products have been classified into Component Based Products (CBP) and Feature Based Products (FBP), and then a method for finding a measure for the magnitude of customization (MOC) per component and feature has been introduced. Two illustrative examples have been included to clarify the method. Section 3.3.3 shows how the outcome can be enhanced

by including the work of (Hsuan, 1999) regarding interface constraints, which addresses the fraction of infeasible product combinations.

3.3.1 Product Structure for an MC System

In a mass production system, products are normally composed of standard components that make up the final integral product. On the other hand, in an MC system, the end product typically consists of a set of components or modules that are designed and assembled to fit a particular order. To modularize an existing standard end product it needs to first be decomposed into its finest level of components (elements). Modules are then constructed out of sets of basic elements in such a way to have compatible modular interfaces. The modules are then analyzed in terms of ease of assembly, maintainability, interface constraints and capability of variant generation. Those steps can be repeated until the most efficient modular structure is achieved (Figure 3.7).
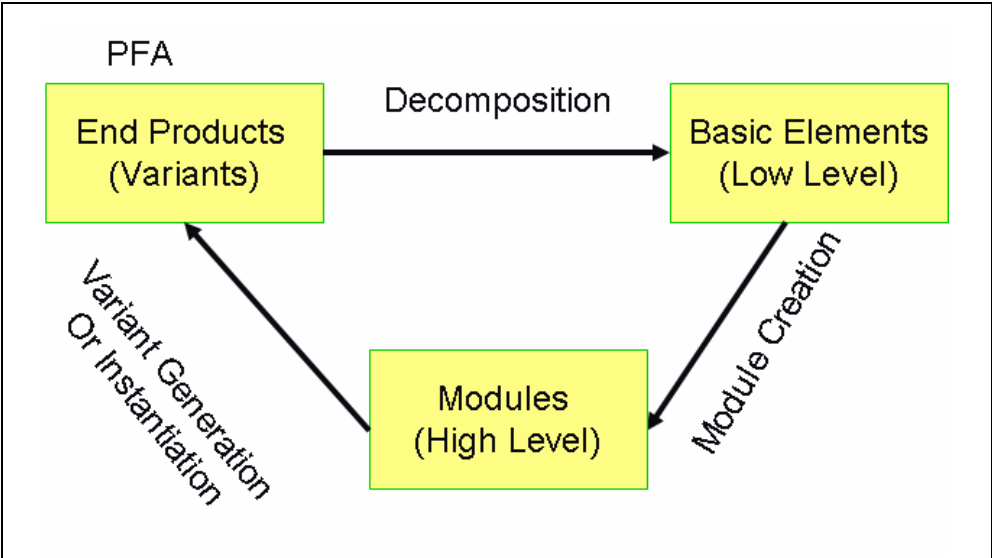
Figure 3.7 Decomposition of product to reconstruct modules for variant generation.

While designing the modular structure, the granularity, which is the module size relative to the end product or system, needs to be considered (Duray *et al*., 2000). Granularity affects the potential degree of customization that can be reached. A finer granule size provides more grounds for a larger number of variants that can potentially be generated; but, in the meantime, the associated manufacturing cost becomes higher. On the other hand, a larger granule size offers less opportunity for variant generation. It must be noted that fine granularity does not necessarily imply a high degree of customization It only paves the way for a higher level of customization. For example, a product that consists of 100 standard non-customizable components has a lower degree of customization than a similar product that only has five but customizable components, where each of those components has a number options or features for the customer to select from. Naturally, if the product had 100 customizable components, it would have a higher capability of variant generation, and hence, a higher degree of customization than the five customizable component case.

3.3.2   Types of Products and Modules

A distinction is made between two types of product families: Component Based Products (CBP) and Featured Based Products (FBP). CBP are mainly seen in built-to-order or assemble-to-order systems, and they have a set of distinct components or modules that can be mixed and matched to compose a family of variants. Each component is allotted a Magnitude of Customization (MOC) value, which is a function of the number of options availed. FBP, on the other hand, represent products in engineer-to-order systems and they include components that have specific features that can be altered within a specific range. These features can be viewed as degrees of freedom that can be controlled based on specific requirements. An MOC value will

also be assigned to each degree of freedom based on the range, scope of increments and importance of the feature.

Upon analysis it has been found that any product appears to be composed of a set of three different types of components or modules: Standard component, Discrete option components, and Features based components (Figure 3.8).
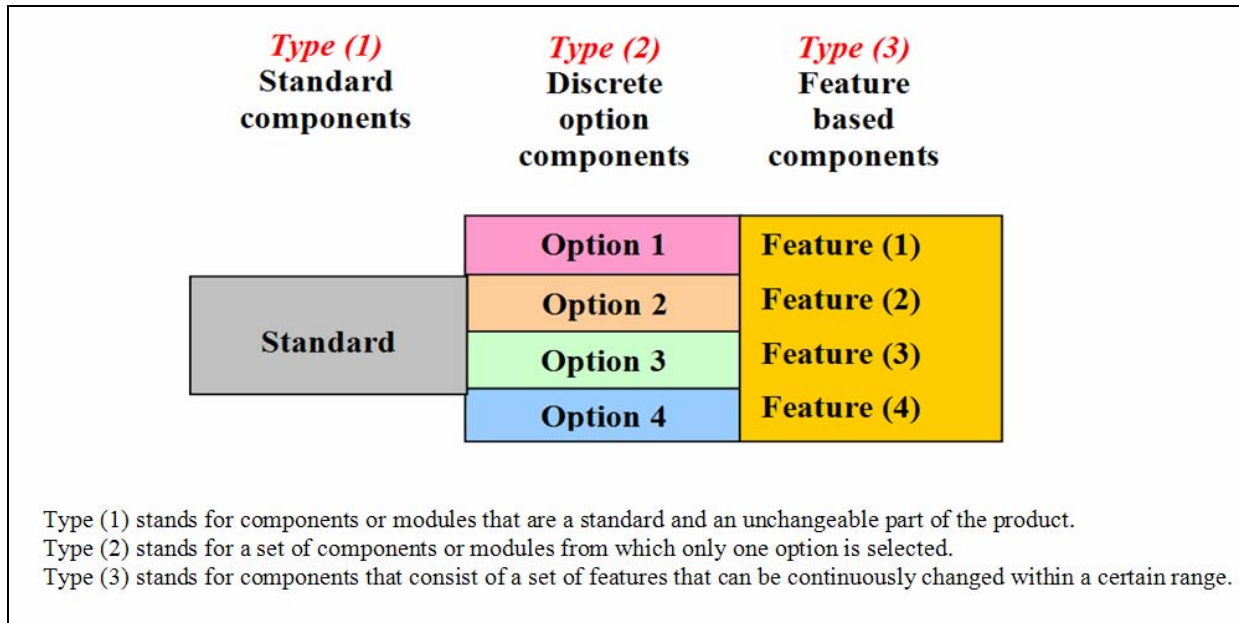
Figure 3.8 Component or module type for a product family.

3.3.2.1   Measuring the Customization level for Component Based Products (CBP)

CBP are only composed of a set of Type (1) and Type (2) components. The Magnitude of Customization (MOC) is the number or a function of the number of potential options for the same component; it represents the degree of customization for this component. The possible combination of all components within a product is referred to as Global MOC (GMOC).

According to Du *et al.* (2000), in an MC system, the products share two elements: First, the "common bases" which represent the standardization aspect of the product that allows for economies of scale. Second, the "differentiation enablers" that facilitate variety generation and

represent the customization aspect of the product, and this promotes economies of scope. The existence of different versions of the same module "differentiation enablers" allows the generation of different variants. Increasing the number of options per component or module, which is also increasing the MOC value, will give a large number of variants that can potentially be generated or a larger GMOC.

The following example shows the structure for a CBP and the method used to determine the degree of customization. Figure 3.9 illustrates a case for a final integral product that is decomposed into 27 basic elements or components. The small cubes indicate the finest elements within the product.
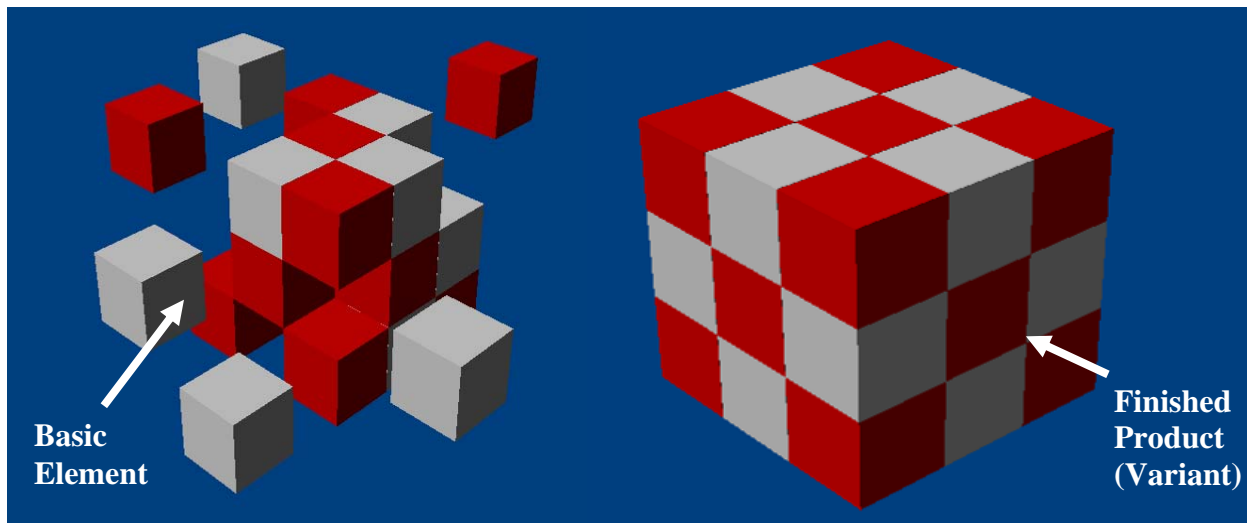
Figure 3.9 The finniest standard element or component in a product.

Figure 3.10 shows six modules that are created from the basic elements. Each of those modules has a variation of four colors. The colors represent different versions for the same module having an assortment of technical, functional, or structural varieties. We can also say that each of the six modules has a Magnitude of Customization (MOC) value of four (refer to Table

3.3). In this example, for simplicity, we assume that all components are used and that there are no interface constraints; that is, there are no restraints to any of the mixes.
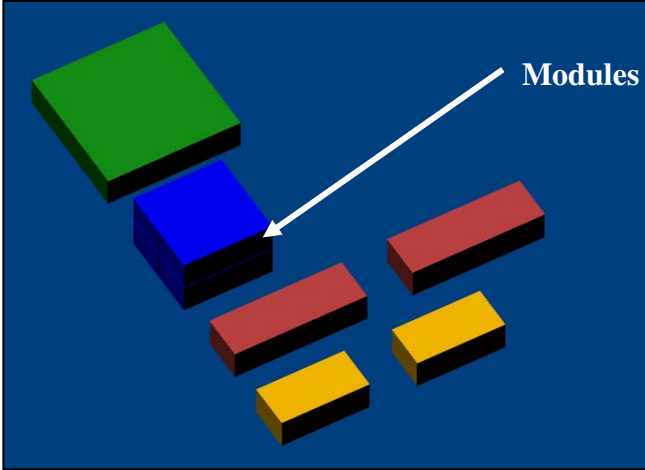
Figure 3.10 Module construction.
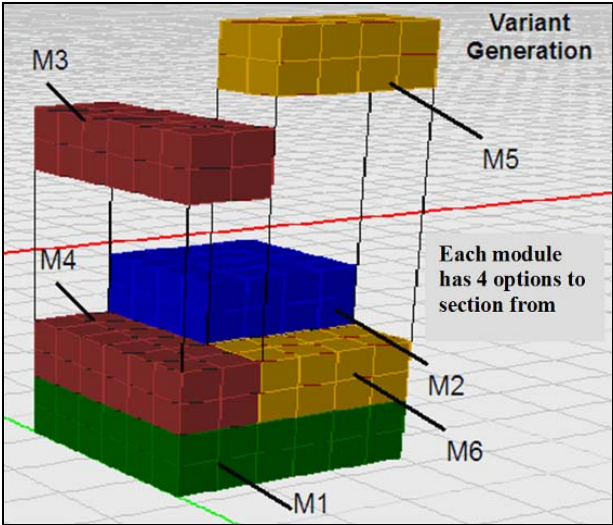
Figure 3.11 Module assembly and configuration.

The total number of combinations or total number of potential variants for a product family can be computed as show by Eq. 3.1, where GMOC is the number of potential variants that can be generated, MOC_i is the number of available options per module (i), and C is the total

number of modules present in the system (final product). The total number of potential variants or Global Magnitude of Customization (GMOC) resulted to 4,096 variants (refer to Table 3.3).

$$GMOC = \prod_{i=1}^{C} MOC_i \qquad (3.1)$$

Table 3.3 The set of modules and their corresponding MOC - (Case -1).

Module	Number of elements per module	Number of distinct module options (MOC)
M_1	9	4
M_2	8	4
M_3	3	4
M_4	3	4
M_5	2	4
M_6	2	4
GMOC		**4,096**

The customization scale (CS) introduced in Section 3.2.1 represents the degree of customization (C_z) as a percentage or fraction from 0 to 1. When C_z is zero, it reflects a standard product with no variation or customization. As the GMOC increases the degree of customization tends to unity. In essence, 100% customization is an abstract notion as there are always grounds for more customization. The degree of customization can be increased until it reaches a stage where further increasing the level of customization will barely contribute to any significant or noticeable value-added to the customer, but will only render the producer higher production costs. This behavior shows a diminishing value-added perceived by the customer as customization increases.

Two different approaches are considered for converting the GMOC to a C_z value ranging from 0 to 1:

First, is using an asymptotic conversation function (Eq. 3.2) where as the GMOC increases C_z asymptotically tends to unity. This type of function will include a constant scale

factor τ that is an arbitrary value proportionate to the order of GMOC values obtained. That is a product family having GMOC values in the thousands would possibly require a τ constant in the thousands, whereas, another category of product family having GMOC values in the billions would need a τ constant in the billions. Figure 3.12 shows the effect of different τ values on the asymptotic conversion function. This value might vary depending on the structure of the product and the nature of the industry. Once a τ constant has been determined for a particular category of products it should not be changed so as to keep a base for comparison and benchmarking.

$$C_z = 1 - e^{(-GMOC/\tau)}, \quad \text{where } 0 \le C_z < 1 \tag{3.2}$$
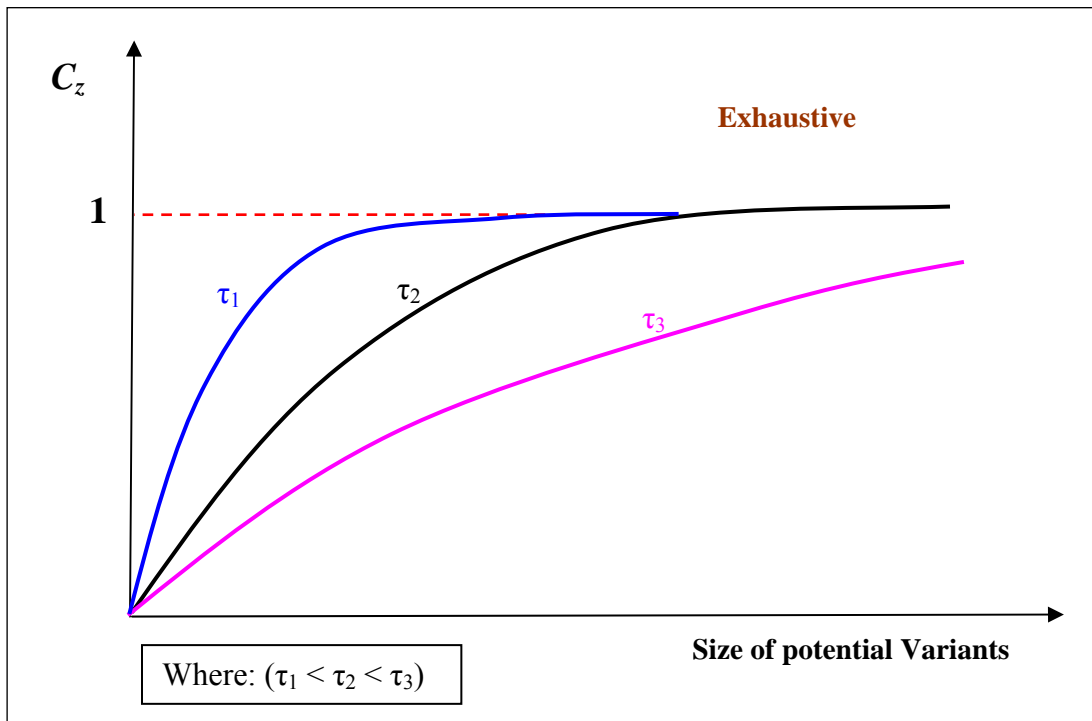
Figure 3.12 The degree of customization (C_z) as a function of the GMOC.

Second, is employing a logarithmic conversion function that is relative to a predefined maximum degree of customization (Eq. 3.3). As has been mentioned earlier there is no absolute GMOC that we can physically define. However, the manufacturer can set a maximum global magnitude of customization (GMOC$_{max}$) by determining a limiting MOC value or MOC$_{max}$ for each component and feature within the product. We define the MOC$_{max}$ as the maximum level of customization technically or structurally feasible given the current technology. It can also be referred to as the point beyond which the manufacture or decision maker would disregard further customizing a particular component or feature. Examples for determining an MOC$_{max}$ could be:

- If further customizing a component or feature would make no significant difference as far as the customer is concerned.

- If there exits some technical reason or policy that prevents exceeding a certain number of options.

- If the cost of customizing beyond a certain point is prohibitive, and the manufacturer would never consider it despite other potential advantages or benefits.

The logarithmic conversation function has been found to be easier to employ by practitioners and is, therefore, elected for use in the following examples and case study in chapter 4. The MOC$_{max}$ is a dynamic value that may change upon the introduction of new technologies, processes or even policies. Therefore, it is imperative to keep track of which MOC$_{max}$ or GMOC$_{max}$ is being used especially when benchmarking product families.

$$C_z = \frac{Log(GMOC)}{Log(GMOC_{max})} \quad \text{where,} \quad (0 \leq C_z < 1) \tag{3.3}$$

In Case 1, we assume that the MOC_{max} is 5 for each module. This means that the producer would disregard having more than 5 selection options for each module. The $GMOC_{max}$ is computed by using Eq. 3.1 to give a value of 15,625. The degree of customization (C_z) for a GMOC value of 4,096 is calculated as shown by Eq. 3.4., which gives 86.14% customization.

$$C_z = \frac{Log(4,096)}{Log(15,625)} = 0.86135 \quad \text{or} \quad (86.14\%) \tag{3.4}$$

Let us assume another case (Case-2) for the same product, but with a higher number of options, or MOC values, for the same modules (Refer to Table 3.4). The total number of potential variants or GMOC becomes 6,400 variants.

Table 3.4 The set of modules and their corresponding MOC - (Case -2).

Module	Number of elements per module	Number of distinct module options (MOC)
M_1	9	4
M_2	8	4
M_3	3	4
M_4	3	4
M_5	2	5
M_6	2	5
GMOC		**6,400**

Considering that the $GMOC_{max}$ is the same for both cases (15,625), we then compute the C_z for that case which gives 90.76% customization, as shown by Eq. 3.5. We notice that the C_z is higher in Case 2 than in Case 1.

$$C_z = \frac{Log(6400)}{Log(15,625)} = 0.90757 \quad \text{or} \quad (90.76\%) \tag{3.5}$$

3.3.2.2   Measuring the Customization level for Featured Based Products (FBP)

Typically, FBPs are composed of a set of Type (1), Type (2) and Type (3) components. Calculating the degree of customization will be slightly different from the technique used for CBPs. Some components or modules may contain features that can be continuously controlled within a specific range such as, for instance, cut sizes. That will in turn generate an infinite option combination which will result into a false indication for the degree of customization. To demonstrate the technique, we use the example of a candlestick, as shown in Figure 3.13. The product consists of three customizable components: the base, rod, and candle holder. The fourth component, which is the connection adaptor, is a standard non-customizable component. The base and candle holder include various optional artistic shapes to choose from. We assume that both the candle holder and base can be mounted to a variable length rod by means of the standard connection adaptors. All three components have an option of 10 different color coatings. Each customer selects the desirable mix of shapes and coating based on his/her taste. FBCs can contain more than one controllable feature; they are also referred to as degrees of freedom (DOF), some of which can be continuously altered.
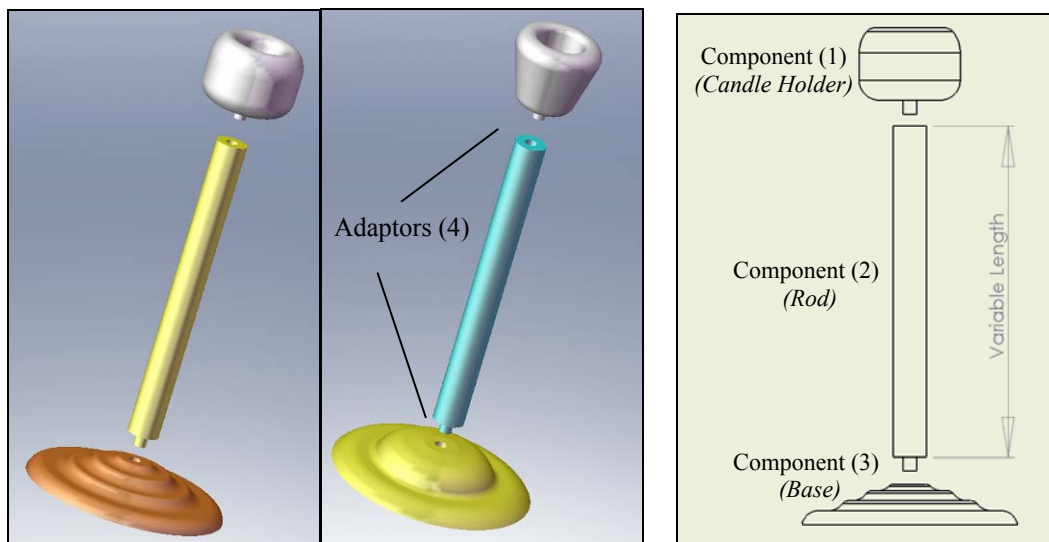
Figure 3.13 A Candlestick composed of three customizable components.

We shall consider two scenarios for this example, each at a different degree of customization. In the first scenario, as presented in Table 3.5, the manufacturer offers a choice of 20 distinct styles for the candlestick base (component 1), 15 model choices for the candle holder (component 3), and a rod (component 2) that comes at only five different cut lengths or heights. The adaptor (component 4) is a standard component that does not affect the degree of customization and hence is assigned an MOC value of 1. Each of the first three components is offered at a choice of 10 different coating colors independently. The total MOC value for each component is the product of the MOC values for each degree of freedom. The GMOC is the product of all MOC values in the table. In order to compute C_z it is necessary to first determine the MOC_{max} values and $GMOC_{max}$ which are presented Table 3.6. We compute the degree of customization for the first scenario, as shown by Eq. 3.5, which resulted to a C_z of approximately 68.4%.

Table 3.5 First scenario - candlestick manufacturing at a lower degree of customization.

Components	Number of identical components	MOC for Feature-1 (DOF-1)	Description	MOC for Feature-2 (DOF-2)	Description	Total (MOC)
Base	1	20	models	10	Coating	200
Rod	1	5	(Length increments)	10	Coating	50
Candle holder	1	15	models	10	Coating	150
Fixing Adaptor	2	1	-	1	-	1
Global Magnitude of Customization (GMOC) …						1,500,000

Table 3.6 The candlestick manufacturing at a maximum degree of customization (MOC_{max}).

Components	Number of identical components	MOC_{max} for Feature-1 (DOF-1)	Description	MOC_{max} for Feature-2 (DOF-2)	Description	Total (MOC_{max})
Base	1	40	models	30	Coating	1200
Rod	1	25	(Length increments)	30	Coating	750
Candle holder	1	40	models	30	Coating	1200
Fixing Adaptor	2	1	-	1	-	1
Maximum Global Magnitude of Customization ($GMOC_{max}$) …						1,080,000,000

$$C_z = \frac{Log(1,500,000)}{Log(1,080,000,000)} = 0.68369 \quad \text{or} \quad (68.37\%) \tag{3.5}$$

For the second scenario, as shown in Table 3.7, the number of Base model options has been increased to encompass 30 models corresponding to an MOC of 30 for this degree of freedom (DOF). Also, the rod length has become custom on a continuous basis instead of having five distinct cut lengths, as in the first scenario. For example, customers may need specific candlestick heights to fit the interior design decoration for their homes that may not lie among the five fixed lengths previously offered. For the current situation a limiting MOC value (MOC_{max}) of 25 is assigned to this DOF. Determining this value may require expert analysis. One reason for choosing this number, for instance, would be that beyond 25 cut increments it would make no significant difference to the customer's naked eye, as far as interior design is concerned; having thousands of increments would be as good as having 25. Other factors, such as the importance of this feature and its impact on the customer selection or design process, govern the choice for the MOC_{max} value. Table 3.6 lists all MOC_{max} values for each component or feature. Adding an extra DOF or feature, such as a choice of rod diameter, would require an additional column describing the same component.

Table 3.7 Second scenario - candlestick manufacturing at a lower degree of customization.

Components	Number of identical components	MOC for Feature-1 (DOF-1)	Description	MOC for Feature-2 (DOF-2)	Description	Total (MOC)
Base	1	30	models	10	Coating	300
Rod	1	25	(Length increments)	10	Coating	250
Candle holder	1	15	models	10	Coating	150
Fixing Adaptor	2	1	-	1	-	1
Global Magnitude of Customization (GMOC) …						11,250,000

$$C_z = \frac{Log(11{,}250{,}000)}{Log(1{,}080{,}000{,}000)} = 0.78056 \quad \text{or} \quad (78.06\%) \tag{3.6}$$

The calculations, as seen in Eq. 3.6, show that the second candlestick scenario holds a significantly higher level of customization, which resulted to a C_z of approximately 78.1%. Adding more options or increasing the extent of features to any of the components will increase the level of customization even more.

3.3.3   Including the Interface Constraint in Degree of Customization Computations

The computations for this example did not account for the interface constraint. The interface constraint addresses certain combinations that cannot be assembled for technical reasons or other. Those constraints reduce the overall number of potential variants. The formulations developed by Hsuan (1999) are employed to include the effect of the interface constraint. The interface weight of components (w_c) is computed as follows where k_c is the number of interfaces of each component within the module, and k_m is the number of interfaces of each module within the system. w_m is computed similarly and it represents the interface weight of the modules in the system. The formulation is as follows (Hsuan, 1999):

$$w_c = \left[\frac{k_c}{\sum k_c} \right]_m \quad , \quad 0 \le w_c < 1 \tag{3.7}$$

$$w_m = \left[\frac{k_m}{\sum k_m} \right]_S \quad , \quad 0 \le w_m < 1 \tag{3.8}$$

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The interface constraint for each module is denoted by the symbol δ_m, where n_c is the number of components per module. The equation is expressed as follows (Hsuan, 1999):

$$\delta_m = n_c \left[\prod w_c \right]_m \qquad (3.9)$$

The interface constraint for the system is denoted by the symbol δ_s, where n_m is the number of modules in the system. The equation is expressed as follows (Hsuan, 1999):

$$\delta_s = \sum \left[\delta_m \right]_s + n_m \left[\prod w_m \right]_s \qquad (3.10)$$

While C_z stands for the degree of customization, C_r is a more realistic measure for the degree of customization as it includes the effect of the interface constraints.

$$C_r = C_z . \delta_s \qquad (3.11)$$

3.4   Multi-Criteria Analysis for the Degree of Customization in MC Systems

3.4.1   Analytical Optimization Model for the Degree of Customization

To optimize the degree of customization, the tradeoffs between the benefits and costs of venturing into an MC system need to be analyzed. Typically, companies would embark in a detailed decision analysis of whether to venture into MC or sustain a fully standardized mass production system. However, in this research, the aim is not only to make the decision of

whether to introduce an MC system or not, but also to determine how far to customize to be most successful in meeting organizational goals while considering existing limitations. The proposed model incorporates criteria or goals such as customer satisfaction level, budget considerations, risk factors, reputation, safety, ergonomic compliance, medical concerns, environmental issues, outsourcing and others. Such goals may contribute to the profitability of the system in a direct or indirect way. There are a few challenges associated with such goals. First, the units per goal are not always easily converted to dollar values. Second, not all the requirements can be dealt with simultaneously.

Goal programming (GP) has been found to be a suitable optimization technique for such a problem. Organizational goals can be formulated in the form of constraints for an objective function that will try to minimize the deviations from these goals. By using preemptive GP, each goal or set of goals can be considered each at a time sequentially. For that the goals need to be ranked based on importance in a hierarchical manner. However, the drawback is that the initial goals may have a dominant effect on the goals to follow and therefore the goals prioritization need to be carried out carefully. The next section considers some ranking techniques that may be useful for this application. Dealing with each goal at a time makes it easier for the management to set their aims, expectations and resource limitations in advance. Based on that, the management can determine the most appropriate degree of customization at which to venture. This model also offers the flexibility of including additional goals, if necessary.

The following are examples of some important goals that can be taken into account when deciding how far a firm or organization intends to embark in an MC system:

Goal 1 = Target premium price for the product or target increase in customer satisfaction.

Goal 2 = Additional market niches that needs to be captured as "percentage"

Goal 3 = Improve ergonomic conditions for health issues (product for physiotherapy).

Goal 4 = Improve environmental consideration.

Goal 5 = Acceptable safety level

Goal 6 = Reduce Outsourcing of components

Goal 7 = Acceptable risk level

Goal 8 = Maximum level of component inventory that can be availed

Goal 9 = Budget constraint or investment allocation

Goal 10 = Availability of raw material and the extent of suppliers' flexibility

Goal 11 = Market preferences based on a wide market research

Goal 2 = Target savings in reduction of Finished Goods Inventory (FGI)

Goal 13 = Target savings in reduction of forecasting plans for product demand

Goal 14 = Target savings in reduced product returns

Goal 15 = Acceptable quality level

Goal 15 = Acceptable brand Dilution level.

Goal 16 = Environmental Concerns.

Goal 17 = Minimum Level of Safety.

3.4.2   Prioritization of Strategic Objectives Targeted through Mass Customization

In this section, we are looking for a simple but effective way to rank the organizational goals in order of importance. There are mainly two challenges: First, more than one decision-maker is typically involved in the process, each having different subjective views. Decision-makers may also rely on expert opinions, whether Marketing Managers, Production Managers, or Consultants. Each of them views MC from a particular angle. Secondly, the organization goals

can be manifested in different disciplines such a customer satisfaction, customer loyalty, health concerns, risk, reputation, budget limitations, technological capabilities, and others. It is challenging and undesirable to merge such criteria under a single representative unit. For example, human life is hard to express in dollars or unity, and need to be prioritized and considered separately.

Several potential ranking techniques are listed and compared in Table 3.7. The columns include a brief description of each technique, the application they are typically involved in, whether there is a need to unify the criteria units and types of inputs/outputs (Cooke, 1991; Alldredge *et al.*, 1992; Danials *et al.,* 1997; Jia *et al.*, 1997; Saaty, 1990; Saaty, 1996).

Table 3.8 Comparison of different techniques for goals ranking.

Ranking Techniques		Brief Description	Applications	Sharing Same Units	Input Requirements per alternative	Output Results per alternative
Data Envelopment Analysis	(DEA)	Tool used to measure efficiencies across firms or organization	Commonly used to evaluate the efficiency of a number of best practices when compared with a virtual best practice.	Yes	Multiple	Single
Equal Weighting Method	(EW)	Multi attribute decision making process but with unbiased judgment	Stocks, ranking countries or car pollution emissions	Needed	Multiple	Single
Budget Allocation	(BA)	The impact alternatives have on issues and concerns (activities) are identified and a score is generated. Activities are then compared on a benefit-cost ratio basis.	Capital investment. Project selection and prioritization	Yes	Multiple	Single
Analytic Hierarchy Process	(AHP)	This technique is based on pair-wise comparison of different criteria, and establishing a degree of relative importance between each pair of criteria. The outcome includes a consistency rating.	Ranking of evaluative criteria used to decide between alternatives such as: projects, asset purchases or others	Not necessarily	Single	Single
Analytic Network Process	(ANP)	ANP is complementary AHP. It allows both interaction and feedback within clusters of elements (inner dependence) and between clusters (outer dependence). Such feedback best captures the complex effects of interplay in human society, especially when risk and uncertainty are involved.	ANP is applied to a large variety of decisions including marketing, medical, political, social, forecasting and others.	Not necessarily	Single	Single
Nontraditional Capital Investment Criteria	(NCIC)	This technique is similar to AHP; however, the relative importance of criteria is interpreted in monetary terms.	Used mainly for investment related decision making.	Yes	Single	Single
Psychological Scaling Models: Paired Comparison		This technique is similar to AHP in the use of pair-wise comparisons. However, it takes in consideration the relative consistency rating for "n" experts who may not be in accordance.	Ranking of evaluative criteria used to decide between alternatives such as: projects, asset purchases or others	Not necessarily	Single	Single

Data Envelopment Analysis is a popular technique that is typically used to evaluate best practices especially when compared to an ideal or virtual best practice. The technique evaluates the criteria base on a number of sub-criteria defining each criterion. In our case, we may not have several sub-criteria to start with (Danials *et al.,* 1997). *Equal Weighting* is also a multi-attribute decision making tool that is unbiased to its sub-criteria (Danials *et al.,* 1997). In our case, bias is not an imminent concern especially that we are dealing with subjective expert opinions, some of

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whom may be more reliable than others. In our ranking process we try to avoid resorting to unit unification. Budget allocation is a technique that requires multiple inputs and unification of units. In our model we only deal with single inputs from the experts. This leaves us with three suitable candidates for ranking the goals: First, is AHP which has been introduced by Saaty (1990). Second, ANP, which is a complementary technique to AHP, also developed by Saaty, (1996), that considers correlations between criteria. Third, is Psychological Scaling Models: Paired Comparison (Cooke, 1991, p. 211), which is derived from the AHP technique.

The following are the advantages of these three techniques:

- The criteria units need not be unified.

- Only a single input is needed for the pair-wise comparison process, which is: how better is one criterion versus the other.

- Consistency analysis is performed in both cases to assess the judgment of experts. Cooke's (1991) technique uses a weighting method that gives higher credit to more consistent experts.

Since, in our research, we are confined to the categorization of the organizational goals in order of importance, we shall only use the pair-wise comparison demonstrated in Analytical Hierarchy Process (AHP) as a means of ranking.

3.4.3   The Goal Programming Model

An algorithm for the model consisting of 8 steps is show in Figure 3.14. The first five steps need to be followed before applying the GP model which is Step-6. Step-7 and Step-8 deal

with converting the outcome of the GP model to a meaningful solution for production planning and for use by the upper management or stakeholders as a benchmarking tool.

In Step-1, as seen in Sections 3.4.1, the company needs to set its organizational goals and specify target values for each goal. For example, in *Goal 1*, as mentioned in Section 3.4.1, the management may want to augment the level of customer satisfaction through MC up to a specific target value. This value may be determined in *Utilities* or *Units of Satisfaction*. For *Goal 2*, the objective may be to increase the market niches to be captured. This value may be specified as an additional percentage of the existing market niches targeted. For *Goal 7*, the management may decide on a minimum acceptable risk index. For *Goal 9*, the stakeholders may decide on a maximum amount of funding dedicated for the application of an MC system. This amount would be probably set in dollar values.

In Step-2, the Operations Department needs to be consulted to determine which product components and features can potentially be customized. Then, by implementing the techniques developed and presented in Sections 3.3.2.1 and 3.3.2.2, each component and feature will be assigned a quantification scale in MOC units. The MOCs will be the decision variable that we attempt to solve for.

In Step-3, experts from many departments including the Operations, Marketing, and Finance department need to collaborate to determine the MOC contributors pertaining to each goal. The contributors are the coefficients or functions corresponding to each decision variable in each goal expression.

In Step-4, the rigid constraints are identified, which are problem limitations or boundaries that are not subject to deviation. Such constraints include technical or structural restrictions that must be respected.

In Step-5, we deal with the prioritization of the goals that were defined in Step-1, in order of importance. In some cases goals may share the same priority level and carry different weights. In that case those set of goals will fall under the same objective function and be solved simultaneously. Once the goals are prioritized specific target values need to be determined for each goal.

In Step-6, the GP model is applied by using the general form expressed by Eq. 3.12 and Eq. 3.13. The model solves for the first priority level; and if the solutions outcome yields a deviation that is within the permissible range, this goal becomes a rigid constraint and the model solves for the successive goal, and so on. If any of the deviations form the targets is unacceptable, the goals may be re-prioritized or some of the rigid constrains may be me reconsidered, then the model is re-executed. This process may need several iterations until a feasible or acceptable solution is achieved. The outcome of the model, which is the set of MOC solutions, is converted to meaningful values through Step-7 and Step-8.

Below is the preemptive GP model, which is structured into a general objective function, a list of goals having specific target values, and a set of rigid constraints. Table 3.9 includes a list of annotations for the expressions and variables used by the GP model.

Table 3.9 List of annotations for the goal programming model.

Annotation	Description
C_z or C_r	Degree of customization (as a percentage or fraction).
i	A component or module within the end product, $i = 1, 2, 3, ... , c$
j	A customizable features or DOF within each component (i), where $j=1,2,3, ... ,f$ (Note that f=1 for discrete option components).
MOC_{ij}	Magnitude of Customization per component or module (i), where (j) is the feature per module or component (i). (Note that $j=1$ for discrete option components) – The decision variables.
W_{lij}	Weight of each component (i) and feature (j) corresponding Goal (l).
R_{lij}	Sensitivity of each component (i) and feature (j) corresponding Goal (l).
$Goal(l)$	Specific target value for the goal, where $l= 1,2, 3, … N$.

Annotation	Description
$F_{lij}(r_{lij}, w_{lij})$	Contribution function or coefficient for each MOC_{ij} per each $Goal(l)$.
$MOC_{(max)ij}$	Limiting (maximum) values set by the producer for each MOC_{ij}.
$GMOC_{(max)ij}$	Limiting (maximum) GMOC which is the product of each $MOCmax_{ij}$.
P_l	Priority or ranking of $Goal(l)$.
d^+, d^-	Positive or negative deviation from target – We assume the deviation to have weights of 1.

Objective function:

$$\text{MIN} \sum_{l=1}^{N} P_l((-d_l^+)or(+d_l^-)) \tag{3.12}$$

Goals:

$$\sum_{i=1}^{c}\sum_{j=1}^{f} F_{lij}(r_{lij}, w_{lij})MOC_{ij} + d_l^- - d_l^+ = Goal(l), \tag{3.13}$$

where $(l = 1, 2, 3 \ldots N)$, $(i = 1,2,3 \ldots C)$, $(j = 1,2,3 \ldots f)$ and $(MOC_{ij}, r_{lij}, w_{lij}, d_l^-, d_l^+ \geq 0)$

Rigid Constraints:

There are two types of constraints that are considered: First, are the upper-limit

constraints that are set by the producer which are referred to, in Section 3.3.2, as MOC_{max} values.

In other words, those are the MOC values that the manufacture would not want to exceed and are

expressed as follows:

$$MOC_{ij} \leq MOC_{(max)ij} \text{ where, } (MOC_{(max)ij} \leq 1) \tag{3.14}$$

Relationship Constraints:

The second type of constraint defines relationships between the scopes of variation of one

component or feature with respect to other components or features as expressed in Table 3.10.

Table 3.10 General formulation for the relationship constraints

	MOC1	MOC2	MOC3	MOC$_{i,j}$	MOC$_{c-1,f-1}$	MOC$_{c,f}$
MOC1		X$_{[1,2]}$	X$_{[1,3]}$	X$_{[1,(i,j)]}$	X$_{[1,(c-1,f-1)]}$	X$_{[2,(c,f)]}$
MOC2			X$_{[2,3]}$	X$_{[(2,i,j)]}$	X$_{[2,(c-1,f-1)]}$	X$_{[2,(c,f)]}$
MOC3				X$_{[3,i,j)]}$	X$_{[3,(c-1,f-1)]}$	X$_{[3,(c,f)]}$
MOC$_{c-1,f-1}$						X$_{[(c-1,f-1),(c,f)]}$

Where, $\{-1 \leq x \leq 1\}$

The variable *x* has a range of $\{-1 \leq x \leq 1\}$ and it represents relationships, that need to be defined, between the MOC of each component or feature with other components or features in the system. A value of "-1" signifies that two features or components' MOC are inversely proportional, a value of "0" means total independence between components' or features' MOC and a value of "1" implies that two features' or components' MOC are directly proportional.

The algorithm in Figure 3.14 demonstrates the steps required to prepare for and apply the preemptive GP model and the steps for results interpretation to develop recommendations for the best degree of customization for a product. Before starting the model, extensive research is necessary to obtain accurate estimates for the contribution functions $F_{kij}(r_{kij}, w_{kij})$ or reliable coefficients for the decision variables. The quality of the contribution function will highly affect the model solution.
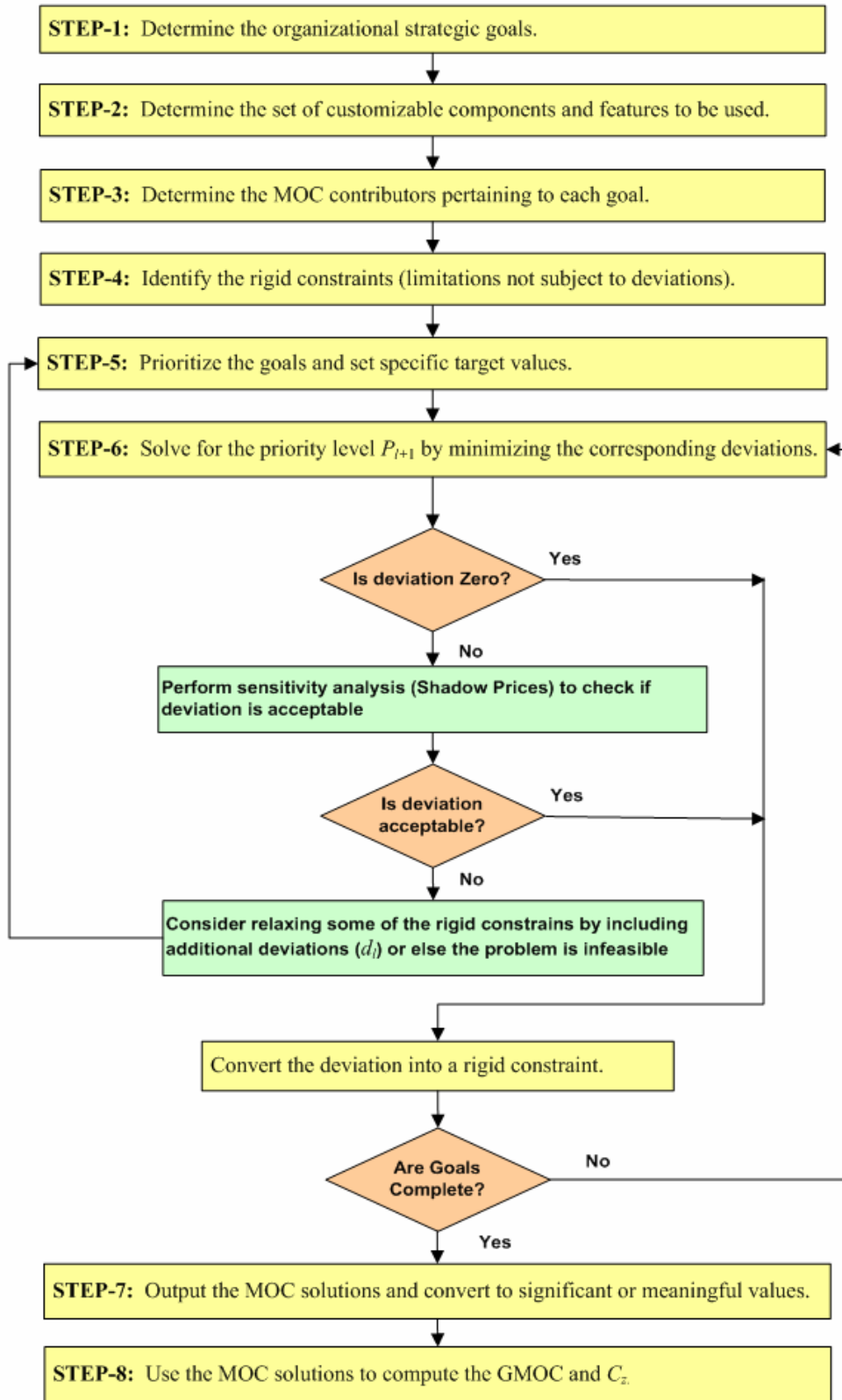
Figure 3.14 Goal Programming Modeling Algorithm solving for the MOC values.

The GP model is applied incrementally solving one goal at a time. In each step the decision-maker will get the chance to accept or reject a possible goal deviation. Acceptance would mean proceeding to the next goal. In case of rejection, the decision-maker may want to reconsider the priority of the goals or reassess the target values for the goals. The model is then applied again in an iterative form until the goals are completed. It is also possible that the model does not converge. That is neither is the deviation acceptable nor is the decision-maker is willing to reconsider the goal priorities or target values set. That situation would imply a significant conflict of goals where no feasible MOC solution exists.

3.4.4   The Expected Outcome of the Model

The results provided by the GP model should give the MOC values corresponding to each component or feature, based on the goals identified and their assigned priorities. If an MOC value is high, it would emphasize increasing the variation or number of options for the corresponding component or feature. If the MOC for a particular component or feature receives a value of zero, it means that customizing it is highly discouraged. This component or feature should be either eliminated or made as a single standard component if it is a basic part of the product. This information may be vital during the production planning phase of an MC system.

The Global Magnitude of Customization (GMOC) is determined by combining every single MOC in the system. The interface constraints between the MOCs depend on the structure of the product and the logic behind it. The GMOC is then converted to a degree of customization (C_z) by using the logarithmic conversion formula (Eq. 3.3) shown and discussed in Sections 3.3.2 and 3.3.4.

$$C_z = \frac{Log(GMOC)}{Log(GMOC_{max})} \qquad\qquad (3.3')$$

The degree of Customization is only a general figure that offers a benchmarking basis for the upper management and decision-makers to develop a feel of how far the company is involved in MC in comparison to other similar companies in the same industry.

CHAPTER 4: CASE STUDY FOR AN ALUMINUM WINDOWS AND DOORS COMPANY

4.1   Overview of the Case Study

In this chapter we use a case of an aluminum windows and doors company for model validation. This company is specialized in the manufacturing of aluminum sliding windows and doors that would meet the demands of new impact glazing codes. Their high standards for performance and aesthetic requirements led to the development of the Series 8000 Sliding Glass Door. The company now has over 250 employees and occupies 310,000 square foot manufacturing facility. My six years of experience in the aluminum windows and doors industry made me inclined to select this company and category of products which I am most familiar with.

Double panel sliding windows and doors have been selected as test vehicle for the analysis. Aluminum window and doors manufacturers are sometimes hard to categorize as job shop manufacturers, mass producers or mass customizers. It really depends on the activity in which they are. In some cases, the manufacturer is undergoing projects that may include fancy villas that contain a set of custom designed windows with mix of colors and sizes. In other cases, the company engages in projects that involve resorts or major hotels, where hundreds or thousands of identical windows and doors are manufactured. Upon demand, the manufacturer mixes and matches or adds value to existing components, to compose personalized items. Therefore, we can also label them as an MC company or BTO system, which is under the

umbrella of MC. In this chapter, we do not attempt to categorize the manufactures. Our focus is

on the degree of customization of the product at a component/feature level.

In collaboration with an aluminum windows and door manufacturer, information has

been gathered from the upper management including the Marketing and Finance Department. In

addition, technical data about the product structure have been provided by the Operations

department. The data were collected by means of interviews and questioners, and were used for

the model formulation.

The flow of this chapter is organized in the following order:

Section 4.2 describes the process of gathering information from the manufacturer and the

structure of the questionnaire used. The succeeding sections will closely follow the sequence of

steps described by the model algorithm shown in Chapter 3, Figure 3.14. Section 4.3 involves

identifying the organizational goals, prioritizing them and setting specific target values, which

corresponds to Step-1 and Step-5 of the model algorithm.

In Section 4.4 we demonstrate the technical structure of a double panel sliding window,

which is our test product, and it includes an outline of all components in the BOQ that are used

during the manufacturing process. In Section 4.5, a list of potentially customizable components

and features are selected to be used in the model, leaving out all standard components or

features, which corresponds to Step-2 of the model algorithm. Conversion expressions are then

set for each identified component and feature on an MOC scale. Section 4.6 deals with

determining the MOC contribution to each goal that has been identified, which corresponds to

Step-3 of the model algorithm. The contributions are set on a 0 to 5 scale. This helps obtaining

the coefficients used in the GP formulation.

Section 4.7 deals with the general formulation and application of the GP model. The model formulation includes setting the objective function, the expressions for the goals and the rigid constrains (Step-4). The decision variables in that case are the set of MOC values. During the model application (Step-6) we treat each goal sequentially and in detail. In Section 4.8, which corresponds to Step-7 and Step-8 of the model algorithm, we convert the model solutions to meaningful values that can be used as recommendations for production and strategic planning.

In Section 4.9 we evaluate the MOC results obtained by GP model, to verify and validate the modeling approach. The validation involves a comparison of the MOC solutions with the actual level of customization of the aluminum windows and doors company being researched.

4.2 Information Collection

An aluminum window and doors manufacturer has been the subject of this case study. Several visits were made to the facility. The management including the CEO helped provide the required information. The company manufactures several types aluminum windows including sliding, hinged, pivot, tilt windows and others. However, we selected the double panel sliding window for our analysis as it constitutes 80% of the sales. During the visits several interviews were conducted and a questionnaire was handed out to collect more specific information. Refer to Appendix B to view a template of the questionnaire used. The questionnaire was designed in a way to collect two sets of data. The first set pertains to the model formulation and includes questions regarding the company's organizational goals and technical details about the product. The second set addresses the current customization status of the company and seeks the management recommendation vis-à-vis the best degree of customization. For the purpose of

validation, it must be noted that while the management provided the information, they were not aware of the model outcome.

One of the challenges that were faced during data collection is that the management was reluctant to divulge any information indicating dollar values. For example, the management would not share dollar figures related to budget allocations, sales, and upcoming investments. In some cases such information may be vital to the model formulation. On the other hand, the management agreed to provide information in form of percentages instead. Those values were used by the model and are further discussed in Section 4.4.3.

The questionnaire included six main subject headings (Appendix B):

1. Identification of the company's organization strategic goals and objective.

2. Pair-wise comparison of goals.

3. Extracting information about the test product (double panel sliding window).

4. Determining customizable components and features and estimating its relative contribution to each goal on a scale of 0 to 5.

5. Setting specific a target for each goal.

6. Actual or recommended customization status for validation.

4.3   Organizational Goals Consideration

4.3.1   Goals Identification (Step-1)

In this section the organization goals are identified. To get a better understanding of where the company is headed, interviews were the best means to communicate that.

Some of the questions asked and information sought includes the following:

- Information on the company mission of statement and the goals set to realize it.

- Information on the means objectives that would help realized the company goals.

- What does the company expect to achieve by venturing in MC?

- Is the company seeking a competitive edge in the aluminum windows and doors industry?

- What are the plans to achieve this competitive edge?

- What is the growth rate? By how much is the company planning to expand their sales in the next five years? How is the company planning to achieve that?

- What is the budget allocation to future investments? What is the portion of that investment is intended to provide more customization to the customer?

- Feasibility studies, cost benefit analysis or market research that were conducted in the past.

- What is the size of yearly operational expenses? What is the portion of that is the company willing to dedicate to increasing or sustaining the level of customization?

The questions above were delivered during an interview in a conversational style. The purpose was to stimulate the management's thinking while trying to understand the orientation of the company. During the interview, the management declared some of the companies' most important goals that are believed to be highly influenced by the level of customization. The management stated that providing the customer with more flexibility of choice and higher ability to personalize their own windows is a key factor the success of their company. The success of

the company is measured by how well their organizational goals are meat, or how closer they become to achieving those goals year after year.

The first step of the model algorithm was completed by identifying the following five goals:

- Investment Infrastructural Costs Consideration.

- Running and Operational Costs Consideration.

- Increased Customer Satisfaction.

- Additional market niches captured.

- Additional Component Storage Area Consideration.

4.3.2   Prioritization of the Goals and Setting Target Values (Step-5)

Once the goals have been identified, it is important to prioritize them in order of importance, and then set specific targets for each goal. It may be noticed that this step comes later in the model algorithm (Step-5). The reason for that is that during the incremental model application, there is a possibility that the management may reconsider the goals ranking or need to loosen some of the target values previously set.

In the questionnaire, the management was asked to compare goals with each other as far as imminence is concerned (Appendix B). The pair-wise comparison part of AHP is later implemented to prioritize the goals. One of the benefits of AHP is that it allows a consistency test, by using the eigenvectors, to ensure the expert/s constituency. If more than one experts is involved in the goal ranking, "Psychological Scaling Models: Paired Comparison" (Cooke,

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1991) may be used in a way to give higher weights to more consistent experts. In case there is a significant interdependency between the goals, ANP may be used to account for that. For simplicity, we assume that the goals are independent, and that there is no major correlation between them. Therefore, the use of ANP would not be essential in this case.

Figure 4.3 shows the values that were filled out by the management in their goal comparisons. The rating is as such: 1 = Equal importance, 3 = Moderate importance, 5 = Essential or strong importance, 7 = Very strong importance, 9 = Extreme importance. The numbers 2, 4, 6 and 8 are intermediate values between two adjacent judgments for when a compromise is needed.

		A	B	C	D	E
Investment Infrastructural Costs Consideration	A	1	3	3	1	1/5
Running and Operational Costs Consideration	B	1/3	1	3	1/3	1/5
Additional Component Storage Area Consideration	C	1/3	1/3	1	1/7	1/7
Increased Customer Satisfaction	D	1	3	7	1	3
Additional market niches captured	E	5	5	7	1/3	1

Figure 4.1 Pair-wise comparisons for the identified goals.

		C	D	E	A	B	P.Vector	Norm.
Investment Infrastructural Costs Consideration	C	1.00	3.00	3.00	1.00	0.20	1.200	0.163
Running and Operational Costs Consideration	D	0.33	1.00	3.00	0.33	0.20	0.533	0.073
Additional Component Storage Area Consideration	E	0.33	0.33	1.00	0.14	0.14	0.286	0.039
Increased Customer Satisfaction	A	1.00	3.00	7.00	1.00	3.00	4.000	0.544
Additional market niches captured	B	5.00	5.00	7.00	0.33	1.00	1.333	0.181
							7.35	0.27

Figure 4.2 Priority vectors are obtained and normalized.

Priority vectors are computed and the values are normalized, to determine the ranking. Figure 4.3 shows the computation process. The eigenvector (λ) is also obtained so as to evaluate the consistence index (*CI*) introduced by Saaty (1990), which is expressed by Eq. 4.1.

$$CI = (\lambda_{\max} - n)/(n-1) , \qquad\qquad (4.1)$$

where $\lambda_{\max}$ is the principal eigenvector, and *n* is the number of arguments or goals. According to Saaty (1990) the comparison matrix will be perfectly consistent when the $\lambda_{\max}$ equals the number of arguments. The results showed that $\lambda_{\max} = 5.6869$. The *CI* resulted to 82.83%, which is accepted. The resulting goals prioritization is as follows:

1. Increased Customer Satisfaction.

2. Additional market niches captured.

3. Investment Infrastructural Costs Consideration.

4. Operational Costs Consideration.

5. Additional Component Storage Area Consideration.

The following part of Step-5 deals with setting specific target values for each goal. Owing to the fact that the management would not provide dollar figures regarding the targets for their goals, we resorted to relative values, or percentages. The "percentage" here refers to a percentage of the maximum that is technically feasible or permissible (GMOC$_{\max}$). For example, let's assume that if the company applies the maximum levels of customization that are

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technologically achievable, to each component and feature, that would imply in our case achieving 100% customer satisfaction due to customization. The management is asked to set the minimum acceptable percentage of the ultimate satisfaction level technically feasible. This concept is further discussed in Section 4.6.

The management agreed to the following goals settings:

- A level of satisfaction of at least 50%

- A market growth in sales of at least 40%

- An additional investment cost of at most 20%

- Additional yearly operational expenses of at most 25%

- Expansion in storage space of at most 60%.

During the model application such values may be subject to deviations. It is up to the management to either accept or reject the deviations.

4.4 General Product Structure

A double panel sliding window is a basic product that most aluminum windows and doors manufactures offer. The main structure includes the following (Figure 4.1):

- A single four-sided frame (at a specific width and height) that is normally fitted into a wall opening.

- Two sliding panels that are composed of heels at the bottom and top, jambs at the sides and interlocks in at the center.

- Two pieces of glass fitted into each panel.

- A set of accessories including the handles, wheels, latches, reinforcement brackets, plugs, rubber gaskets, brushes and other.

It is enough to know the dimensions of the wall opening to prepare the cut lengths of all extrusions and the corresponding set of components needed. The reason is that all extrusion profiles as well as the glass size have known and precise clearance cuts relative to the initial wall opening size. There is a range of coating colors to pick up from. Individual clients typically select a color that matches their interior design. In other cases, such as for commercial buildings or residential complexes, the window color coating is selected in a way to match the architectural designs or landscape. The glass type is mainly dependent on the application and climate of the area. Most of the accessories used are standard except for the handles and sometimes latches, which can change in shape and color.
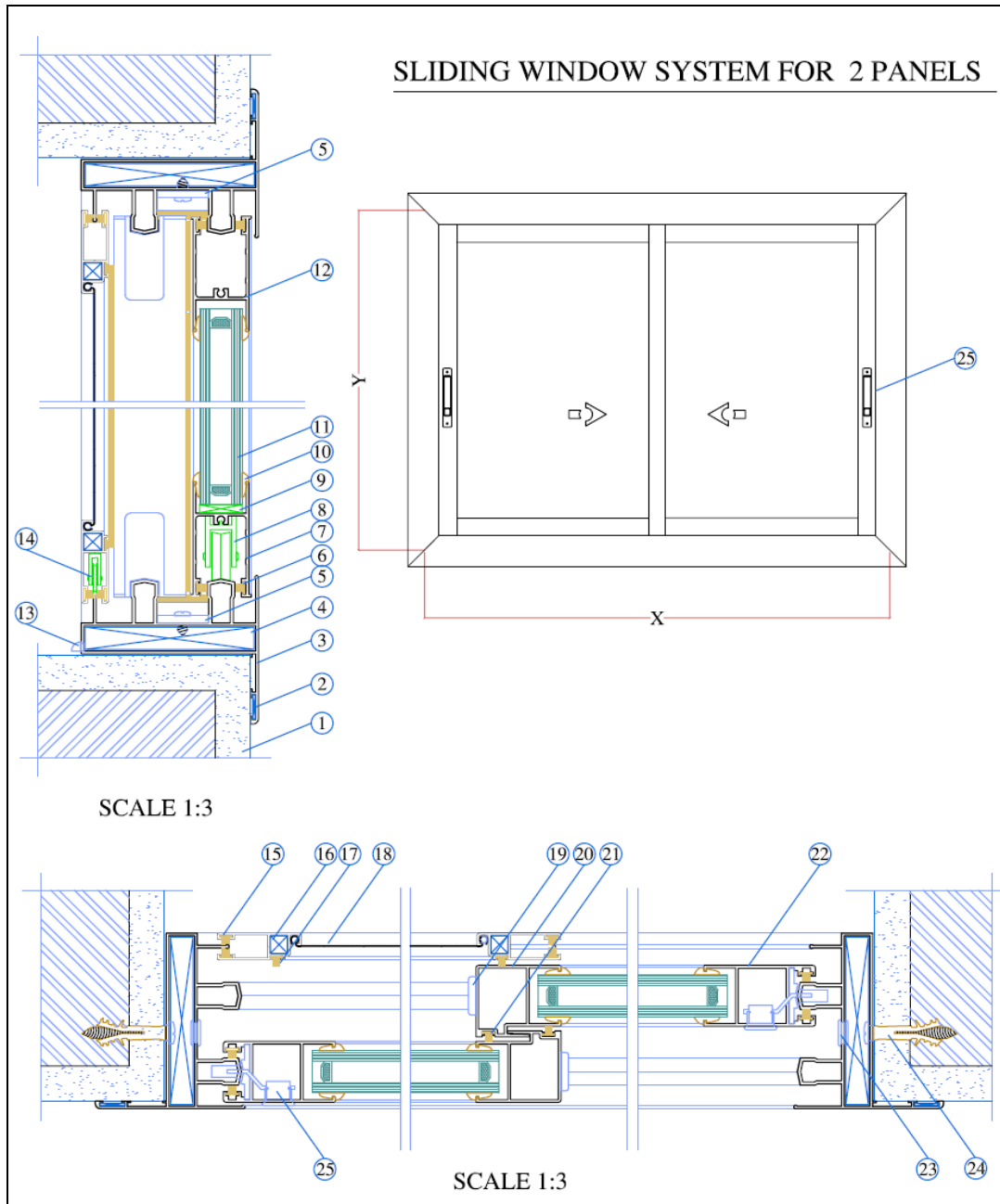
Figure 4.3 Product structure double-panel sliding window.

Figure 4.1 shows the product structure for a double-panel sliding window. Many components are standard, others are customized. We focus, in this case study, on the potentially customizable components and features. Table 4.1 shows a list of all components used in the manufacturing of a double panel sliding window.

Table 4.1 List of components composing the double panel sliding window.

Ref.	DESCRIPTION
1	Straight wall opening having a minimum depth of 100mm or more.
2	Plastic assembly corner for flashing (introduced to profile before crimping).
3	Sliding Frame profile including a 40mm flashing, and a Fly-Screen rail.
4	Aluminum frame assembly corner, 100mm x 20mm thickness. The corner is injected by Epoxy right before crimping. This process guarantees the complete sealing and firmness of the corner.
5	Top and Bottom dust brushes.
6	Reinforced Brushes, on both inner sides of the heals and Jambs to ensure complete sealing.
7	Sliding Panel bottom heal profile.
8	Sliding wheels.
9	Reinforced Plastic Spacer for proper orientation of glass.
10	Rubber Gaskets 3mm thick on both sides of the glass, to guarantee complete seal.
11	Double Glass unit, 24 mm wide. (6mm glass + 12mm spacer + 6mm glass). Double glass offers better heat insulation and sound reduction.
12	Sliding Panel upper heal profile.
13	Drain Hole Cover. This accessory allows better draining, while preventing reverse water flow during rough weather.
14	Fly-Screen wheels.
15	Fly-Screen Inner Brushes.
16	Fly-Screen assembly corner, which is also crimped using Epoxy injection.
17	Fly-Screen Outer Brushes.
18	Fly-Screen galvanized wire net.
19	Plastic side cover for the panel.
20	Sliding Panel Interlock.
21	Imported Reinforced Brushes, on the outer sides of both interlocks, to apply dual sealing at the interlock zone.
22	Sliding Panel Jamb.
23	Rubber Plugs.
24	100mm Screws for tight fixation.
25	Locking Accessories including a coated handle and snapping latches.

4.5 Outline for Customizable Component and Features (Step-2)

As illustrated in Figure 4.2, fourteen customizable components and features were chosen for the analysis. The components include the frame, jamb, interlock, heel, fly screen, rubber gaskets, brush, glass, wheels, handle and brackets. Some components are considered FBCs (Feature Base Components) and may contain multiple features such as type options, coating colors, and cut length increments. Other components are DOCs (Discrete Option Components) and are illustrated in Figure 4.4 as having only one feature which is "Type".

The frame typically comes in three different types (small, medium and large cross-section) each having two additional features: extrusion profile length and coating color. Other extrusions such as the jamb, interlock, heel and fly-screen also have "length" and "coating color" features. However such features are dependent on the frame's features and are, therefore, not accounted for to avoid duplication. For example, if the frame is 65 x 45 inches and yellow, the panels and fly-screen need to be 63 x 43 (exactly two inches shorter than the frame) and also yellow in color. For the same reason, the glass dimensions have also not been accounted for, as they are also a function of the frame size. The handles, on the other hand, include several models each of which can have its own color choice independent of the extrusion coating color. For instance, a client may want to have a yellow-coated window with blue pull handles. Therefore, coating color has been considered as an additional feature for the handle. For simplicity, we assume that all components are FBC and that the DOCs are FBCs having only a single feature, which is the component type.

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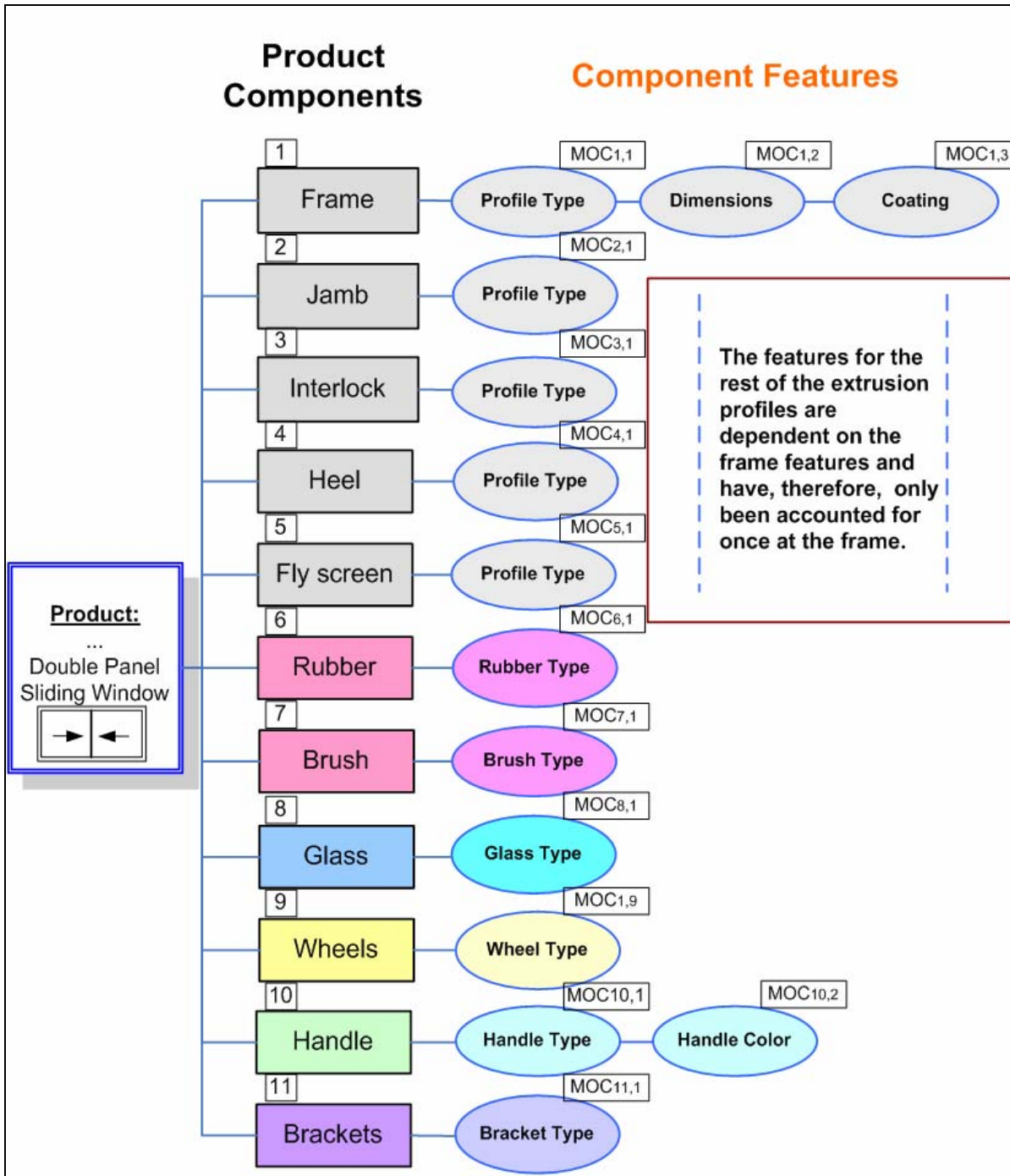
Figure 4.4 Component and feature identification for a double panel sliding window.

As seen in Figure 4.2, each component or feature has been assigned an MOC_{ij}, where "i" stands for the component number and "j" the feature within the component or module. MOC is a measure that represents or is directly proportional to the number of component selection options;

it also indicates the extent or range of each controllable feature within the components. An agreed upon physical or meaningful value for each unit MOC needs to be established based on analysis and expert knowledge about the nature of the components and features. In the case of double panel sliding windows a description of each unit MOC for each component/feature is shown in Table 4.2. The MOC values are translated to physical values by means of expressions as seen at the "Expression" column of Table 4.2. The expression is in the form a step function. For simplicity, we are only dealing with linear or initial portion of the step function. The relationship between the MOC and the corresponding physical interpretation does not necessarily need to be linear. More refined expressions can be set; however, the MOC value must always be proportional to the increase in customization per component or feature.

Table 4.2 Conversion Expressions of MOC to Meaningful or Physical Values.

MOC #	Components and Features		Serial (i,j)	Description	Expression
1	Frame	Type	1,1	A unit MOC stands for a single additional frame extrusion profile. The MOC range is 1-15. MOCs beyond 15 technically unaccepted.	# extrusion profiles = MOC , for {MOC = 1 -15} # extrusion profiles = 10, for {MOC > 15}
2		Profile Length	1,2	A unit MOC stands for a single additional frame cuts or sizes. The MOC range is 1-15. An MOC of 15 and above would imply shifting to continuous custom cuts.	# profile/frame cuts = MOC, for {MOC = 1 -15} # profile/frame cuts = continuous custom cut, for {MOC >= 15}
3		Coating Color	1,3	A unit MOC stands for 50 additional coat Colors. The MOC range is 1-15. An MOC of 15 and above would imply a continuous spectrum of colors.	# coat colors = 50*(MOC), for {MOC = 1 -15} # coat colors = any spectrum of colors, for {MOC > 15}
4	Jamb Type		2,1	A unit MOC stands for a single additional Jamb extrusion profile. The MOC range is 1-15. MOCs beyond 15 technically unaccepted.	# extrusion profiles = MOC , for {MOC = 1 -15} # extrusion profiles = 15, for {MOC > 15}
5	Interlock Type		3,1	A unit MOC stands for a single additional interlock extrusion profile. The MOC range is 1-15. MOCs beyond 15 technically unaccepted.	# extrusion profiles = MOC , for {MOC = 1 -15} # extrusion profiles = 15, for {MOC > 15}

MOC #	Components and Features		Serial (i,j)	Description	Expression
6	Heel Type		4,1	A unit MOC stands for a single additional heel extrusion profile. The MOC range is 1-15. The MOC range is 1-15. MOCs beyond 15 technically unaccepted.	# extrusion profiles = MOC , for {MOC = 1 -15} # extrusion profiles = 15, for {MOC > 15}
7	Fly-screen Type		5,1	A unit MOC stands for a single additional fly-screen extrusion profile. The MOC range is 1-15. The MOC range is 1-15. MOCs beyond 15 technically unaccepted.	# extrusion profiles = MOC , for {MOC = 1 -15}
8	Rubber Type		6,1	A unit MOC stands for a single additional rubber type. The MOC range is 1-15. The MOC range is 1-15. An MOC of 15 and beyond is unnecessary.	# rubber types= MOC , for MOC = {1 -15}
9	Brush Type		7,1	A unit MOC stands for a single additional brush type. The MOC range is 1-15. The MOC range is 1-15. An MOC of 15 and beyond 15 is unnecessary.	# brush types= MOC , for MOC = {1 -15} # brush types = 15, for {MOC > 15}
10	Glass Type		8,1	A unit MOC stands for 5 additional glass types. The MOC range is 1-15. An MOC of 15 and beyond would imply any glass type in the market could be selected.	# glass types = 5*(MOC), for {MOC = 1 -15} # glass types = any glass type in market, for {MOC > 15}
11	Wheels Type		9,1	A unit MOC stands for a single additional wheel type. The MOC range is 1-15. An MOC of 15 and beyond 15 is unnecessary.	# wheel types = MOC , for {MOC = 1 -15}
12	Handle	Type	10,1	A unit MOC stands for 5 additional handle types. The MOC range is 1-15. An MOC of 15 and beyond would imply that a custom handle shape needs to be availed.	# handle types = 10*(MOC), for {MOC = 1 -15} # handle types = a custom handle shape for {MOC >= 15}
13		Coating Color	10,2	A unit MOC stands for 50 additional coat Colors. The MOC range is 1-15. An MOC of 15 and above would imply a continuous spectrum of colors.	# coat colors = 50*(MOC), for {MOC = 1 -15} # coat colors = any spectrum of colors, for {MOC >= 15}
14	Brackets Type		11,1	A unit MOC stands for a single additional bracket type. The MOC range is 1-15. An MOC of 15 and beyond 15 is unnecessary.	# bracket types = MOC , for {MOC = 1 -15}

For example, Item 1 in Table 4.2 refers to the "Type" feature for the window frame. The MOC value corresponds to the number of frame extrusion types. Having four types of frame extrusions would correspond to an MOC of 4. The range of MOC values extend from 1 (one standard frame extrusion) to 15 frame types. We refer to MOC = 15 as the MOC_{max} or upper-limit constraint, which is a technical limitation set by the manufacturer. In the frame case, the manufacturer disregards having more than 15 frame options for technical or other reasons. The same principal applies for the rest of extrusion profiles. In the case of color coating each MOC

unit stands for an additional 50 colors of choice. The MOC_{max} here is also set to 15, which is equivalent to 750 colors to choose from. According to experts, beyond that there is no point of offering additional color selections; it is easier to have the client specify an exact color from a color spectrum and prepare a customized blend.

4.6   Determining the MOC Contribution to the Goals (Step-3)

In this section a detailed analysis and breakdown of each goal is performed to estimate how much each MOC unit will contribute to meeting each target. To be more accurate each goal is reclassified into several areas or means objectives. In this process, we collaborate with the management to estimate the contribution of a unit MOC per component and feature to each of those areas.

4.6.1   MOC Contribution to Marginal Customer Satisfaction

One of the management targets is to be able to sell windows at a premium price. The premium price here refers to the additional price the customer is willing to pay for the customization service that accompanies the commodity. That can also be represented by the marginal or additional satisfaction derived from the customization service. In this section, we are expressing the contribution of each additional unit of MOC to various experiences leading to customer satisfaction. The marginal satisfaction lead by the increase in customization is measured on a satisfaction scale of 0 to 5. The following is a list of sources for customer satisfaction, specific to customization, that have been addressed.

1. Sense of originality: The fact that a customer was able to design or compose a product that is unique to him/her, and that is unlikely to be duplicated, is significantly valued by the customer. Table 4.3 shows estimates for the contribution of increasing the scope of choice, for each component and feature, to the customer's sense of originality.

2. Aesthetic flexibility: The aesthetics of a product is a main contributor to customer satisfaction. The more the flexibility of choice to the aesthetic part of the product the higher the satisfaction level. Table 4.3 shows the contribution per unit MOC, for each component and feature, to the aesthetic flexibility.

3. Artistic influence: Some customers would value being able to express their artistic touch on their product through collaborative customization. Table 4.3 includes the contribution per unit MOC, for each component and feature, to the ability of the customers to articulate their artistic sense.

4. Control over the degree of functionality: Being able to establish control over the degree of functionality of a product is a significant value-added contributing to customer satisfaction. For example, if a customer is able to decide the number of speeds for a custom made bicycle, he/she will chose what best fits his/her application, without spending more on something not really needed.

5. Overall price control: In E-commerce, Customer Relationship Management (CRM) Systems designed for MC systems frequently offer online the corresponding price for

each choice or design made by the customer. Being able to know how choices are affecting the overall price of the product, on a real-time basis, gives a sense of reference and control to the customer while deciding for the order. Here we are looking for the contribution per unit MOC for each component and feature having a widest price range for the customer to select what best fits his/her budget.

6. Delivery time control: Similar to the price control, the ability to influence the delivery time of the product by mixing and matching different choices, on a real-time basis, increases the customers' sense of control and hence satisfaction.

A 0 to 5 scale was used to account for the degree of contribution of each unit MOC to the corresponding source of satisfaction (Table 4.3). On the other hand, some sources may be more significant to the customer than others. Therefore, each source of customer satisfaction has been weighted and normalized based on the importance of that source.

Table 4.3 Contribution of each unit MOC per component/features to customer satisfaction.

	Serial Number (i,j)	1,1	1,2	1,3	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1	10,1	10,2	11,1
		Frame			Jamb Type	Interlock Type	Heel Type	Fly screen Type	Rubber Type	Brush Type	Glass Type	Wheels Type	Handle		Brackets Type
	Components and Features	Type	Profile Length	Coating Color									Type	Coating Color	
WT%	MOC	MOC1	MOC2	MOC3	MOC4	MOC5	MOC6	MOC7	MOC8	MOC9	MOC10	MOC11	MOC12	MOC13	MOC14
25%	Sense of originality	1	5	5	1	1	1	1	1	1	4	0	5	5	1
20%	Aesthetic flexibility	2	3	5	2	2	2	2	1	0	4	0	5	5	0
20%	Artistic Influence	2	3	5	2	2	2	2	0	0	4	0	5	5	0
15%	Control over the degree of functionality	3	5	1	3	3	3	3	3	3	5	3	3	1	3
10%	Overall price control	3	4	1	3	3	3	3	2	2	5	1	2	1	1
10%	Delivery time control	1	3	1	1	1	1	1	1	1	1	1	1	1	0
	Overall satisfaction per unit MOC	1.90	3.90	3.60	1.90	1.90	1.90	1.90	1.20	1.00	3.95	0.65	4.00	3.60	0.80

MOC contribution to different areas of Customer Satisfaction (left vertical label)

Rating Per unit MOC	MOC contributions to different areas of customer satisfaction
0	No contribution per satisfaction area
1	Very low contribution per satisfaction area
2	Low contribution per satisfaction area
3	Significant contribution per satisfaction area
4	High contribution per satisfaction area
5	Very high contribution per satisfaction area

The overall satisfaction owing to customization, which are the values at the bottom of Table 4.3 are also accounted for on a satisfaction scale of 0 to 5. They are expressed by Equation 4.2, where h is the total number of satisfaction sources considered and U_{ij} is the additional satisfaction contribution per unit MOC of each component "i" or feature "j" within each component. The values at the bottom of the table will serve as the coefficients for the left hand side of the *Customer Satisfaction* goal expression. The right hand side is the minimum or target satisfaction set by the management. This target is set as a percentage of the GMOC$_{max}$, maximum satisfaction level allowed by the table. The maximum satisfaction level can be expressed as the sum of coefficients for each MOC multiplied by (15), which is the MOC$_{max}$ assigned to each component and feature in this case study.

$$\frac{1}{h}\sum_{k=1}^{h}(U_{kij}) \text{ , where } (k = 1, 2, 3 \dots h) \tag{4.2}$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(U_{ijk})\right)(MOC_{ij})\right] + d_1^{-} - d_1^{+} = \textit{Target or Minimum Satisfaction level} \tag{4.3}$$

Equation 4.3 represents the level of customer satisfaction targeted, which is subject to a deviation, where c is the total number of customizable components used, and f is the number of existing features per component. For Discrete Option Components (DOC), $f=1$ and it is typically referred to by "Type". The Goal is to minimize (d_1^{-}), which is the negative deviation from the target.

4.6.2   MOC Contribution Additional Market Size Captured

Customization of components and features will enable the producer to fulfill the exact needs of wider and more differentiated market niches. Table 4.4 shows the contribution per unit MOC of each component or feature to the percentage growth in sales in various markets. The following is a categorization of markets for aluminum windows and doors:

1. Commercial buildings contractors.

2. Residential units' contractors.

3. Individuals in the *upper segment*, such as villas or big houses.

4. Individuals in the *middle segment*, mainly condos and large apartments.

5. Individuals in the *lower segment*, such as small apartments or studios.

A 0 to 5 scale is used to account for the degree of contribution of each MOC to the corresponding percentage growth in different market segments (Table 4.4). Some market segments are larger than others. For example, even though the *upper segment* house owners would spend more on customized windows, the *middle segment* housing may be a better target owing to its larger size. Therefore each market segment has been weighted and normalized, based on size and importance, to better reflect the contribution of each unit MOC to the overall market.

Table 4.4 Contribution of each unit MOC per component/features to percentage market growth.

Serial Number (i,j)		1,1	1,2	1,3	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1	10,1	10,2	11,1
Components and Features		Frame			Jamb Type	Interlock Type	Heel Type	Fly screen Type	Rubber Type	Brush Type	Glass Type	Wheels Type	Handle		Brackets Type
		Type	Profile Length	Coating Color									Type	Coating Color	
WT%	MOC	MOC1	MOC2	MOC3	MOC4	MOC5	MOC6	MOC7	MOC8	MOC9	MOC10	MOC11	MOC12	MOC13	MOC14
15%	Commercial Buildings Contractors	3	2	2	3	3	3	3	2	2	4	2	2	2	3
15%	Residential units contractors	2	3	4	2	2	2	2	2	2	3	1	4	4	1
20%	Individuals (Upper Segment)	3	5	5	3	3	3	3	3	3	5	2	5	5	3
35%	Individuals (Middle Segment)	2	4	4	2	2	2	2	2	2	5	1	4	4	3
15%	Individuals (Lower Segment)	1	3	3	1	1	1	1	1	1	4	1	3	3	2
Overall Market Growth per MOC		2.2	3.6	3.75	2.2	2.2	2.2	2.2	2.05	2.05	4.4	1.35	3.75	3.75	2.55

(MOC contribution to sales growth per market sector)

Rating Per unit MOC	MOC contributions to sales growth per market sector
0	No contribution per market sector
1	Very low contribution per market sector
2	Low contribution per market sector
3	Significant contribution per market sector
4	High contribution per market sector
5	Very high contribution per market sector

The overall market growth per unit MOC is represented by the set of values at the bottom of Table 4.4, which are also accounted for on a scale of 0 to 5. The values are expressed by Equation 4.4, where h is the total number of market segments considered and N_{ij} is the percentage market growth contribution per unit MOC of each component "i" or feature "j"

within each component. The values at the bottom of the table will serve as the coefficients for the left hand side of *Market Growth* goal expression. The right hand side is the minimum targeted growth by the management thought MC. The maximum market size can be expressed as the sum of coefficients for each MOC multiplied by (15), which is MOC_{max} value assigned to each component and feature in this case study.

$$\frac{1}{h}\sum_{k=1}^{h}(N_{ijk}) \text{ , where } (k = 1, 2, 3 \dots h) \tag{4.4}$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(N_{ijk})\right)(MOC_{ij})\right] + d_2^- - d_2^+ = \text{ Target or Minimum Total Market Growth} \tag{4.5}$$

Equation 4.5 represents the minimum market growth targeted, which is subject to a deviation, where, h is the total number of market segments considered, c is the total number of customizable components used, and f is the number of existing features per component. For DOC, $f=1$ and it is typically referred to as "Type". The Goal is to minimize (d_2^-), which is the negative deviation from the target.

4.6.3   MOC Contribution to Infrastructural Investment Costs for MC

Infrastructural investment or development costs here mean the portion of costs specific to the customization service. Infrastructural investment costs may include changes in processes, the purchase of new equipment, adoption of new technology, training, research expenses, and other development costs. The higher the level of customization, the company is willing to seek, the larger is the expected size of investment. No matter how keen an organization is to increase their level of customization, there are budget limitations that would size it up. Table 4.5 shows the

dollar contribution per unit MOC for each component or feature to each area of investment on a scale of 0 to 5.

The following is a categorization of different development areas that are considered by the management as MC enablers:

1. Additional Equipment (Machines, Tools)

2. Customer Interface (CRM system)

3. Installing new IT system

4. Advertising

5. R&D

6. Training Staff and Management

7. Extra storage for additional component inventory

Table 4.5 The dollar contribution of each unit MOC per component/features to various infrastructural investment areas.

Serial Number (i,j)		1,1	1,2	1,3	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1	10,1	10,2	11,1
Components and Features		Frame			Jamb Type	Interlock Type	Heel Type	Fly screen Type	Rubber Type	Brush Type	Glass Type	Wheels Type	Handle		Brackets Type
		Type	Profile Length	Coating Color									Type	Coating Color	
	MOC	MOC1	MOC2	MOC3	MOC4	MOC5	MOC6	MOC7	MOC8	MOC9	MOC10	MOC11	MOC12	MOC13	MOC14
MOC dollar contribution per investment area	Additional Equipment (Machines, Tools)	5	2	0	5	5	5	5	2	2	0	0	1	0	0
	Customer Interface (CRM system)	1	1	1	1	1	1	1	1	1	1	1	3	1	1
	Installing new IT system	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Advertising	1	1	1	1	1	1	1	1	1	1	1	2	1	0
	R & D	3	3	1	3	3	3	3	3	3	1	1	1	1	2
	Training Staff and Management	4	2	1	4	4	4	4	3	3	1	2	1	1	2
	Storage for additional component inventory	5	0	5	5	5	5	5	5	5	5	5	2	5	5
Overall Investment cost per unit MOC		2.86	1.43	1.43	2.86	2.86	2.86	2.86	2.29	2.29	1.43	1.57	1.57	1.43	1.57

Rating Per unit MOC	MOC dollar contributions per investment area
0	No dollar contribution needed per investment area
1	Very low dollar contribution per investment area
2	Low dollar contribution per investment area
3	Significant dollar contribution per investment area
4	High dollar contribution per investment area
5	Very high dollar contribution per investment area

To better understand Table 4.5, a few examples are considered:

- Increasing the increments per cut length of the frame (referred to by the blue boxes in Table 4.5) would require a more automated version of the Miter saw which is not much more costly than a regular adjustable Miter saw. In fact the regular Miter saw may do just fine. Therefore, only a "2" (on a scale of 0 to 5) per unit MOC has been assigned to machinery and/or equipment. However, higher variation in frame lengths renders increased R&D investment to come up with systems that will effectively handle the additional complexity; therefore a value of "3" per unit MOC was estimated. On the other hand, increasing the cut length increment does not require additional component storage

area. The frame extrusion profiles are stored in standard lengths and are only cut to the required lengths upon demand; therefore the extra inventory storage cost was assigned a "0", which is no cost at all per unit MOC.

- Increasing the variety in coating color for extrusions (referred to by the red boxes in Table 4.5) requires no additional machinery or equipment. Polyester powder coating entails the same process regardless of the color powder used. The only additional investment would be presented in storage costs for a wider range of color powder containers to have it ready upon demand; therefore a value of "5" per unit MOC was assigned at the "Storage and additional component inventory" row. The same goes for Glass, which are indicated by the green boxes. Different types of glass are ordered directly from the glass manufactures or suppliers; thus there is no need for additional machinery. Storage is the only significant cost that is directly related to an increase in glass variety.

The latter row of Table 4.5 shows the overall dollar contribution of investment per unit MOC for each component or features, which is also accounted for on a scale of 0 to 5. Those values are expressed by Equation 4.6, where h is the total number of different areas of infrastructural investment considered and I_{ij} is an indicator of the amount of budget allocation per unit MOC of each component "i" or feature "j" within each component. The values at the bottom of the table will serve as the coefficients for the left hand side of the *Investment Budget* goal expression. The right hand side is the upper target investment budget allowed by the management for MC. This target is set as a percentage of the upper-limit investment spending

level allowed by the table. The maximum investment spending level can be expressed as the sum of coefficients for each MOC multiplied by (15), which is the MOC_{max} value assigned to each component and feature in this case study.

$$\frac{1}{h}\sum_{k=1}^{h}(I_{ijk}), \text{ where } (k = 1, 2, 3 \dots h) \tag{4.6}$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(I_{ijk})\right)(MOC_{ij})\right] + d_3^- - d_3^+ = \textit{Target or Maximum Investment Budget} \tag{4.7}$$

Equation 4.7 represents the maximum budget targeted for investment, which is subject to a deviation, where c is the total number of customizable components used, and f is the number of existing features per component. I_{kij} is the contribution per unit MOC of a component "i" or feature "j" to the overall investment costs. In the goal expression (Eq. 4.7) we aim at minimizing the positive deviation (d_3^+) and not the negative deviation, as was the case with the previous two goals: Customer Satisfaction and Market Growth.

4.6.4   MOC Contribution to Yearly Operational Costs

By operational costs we mean here costs that relate to additional yearly expenses for customization. This includes increased cost of operation, holding costs for additional inventory capacity, and other running costs. Typically higher levels of customization would reflect higher yearly operational costs in addition to the initial infrastructural investment which was discussed in Section 4.6.3. This goal determines the maximum yearly additional budget allocation that the management is willing to place for the customization service. Table 4.6 shows the dollar

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contribution per unit MOC for each component or feature to each area of operational expenses

on a scale of 0 to 5.

The following is a categorization of different areas of yearly expenses that are necessary for MC:

1. Additional Cost of Operation

2. Additional Component Inventory expenses (holding cost)

3. Cost of new Machinery

4. Cost of additional/more skilled staff/management

5. Increased Cost of Quality Control

6. Increased Cost of Maintainability

7. Induced Complexity Cost

Table 4.6 The dollar contribution of each unit MOC per component/features to various areas of yearly operational expenses.

Serial Number (i,j)		1,1	1,2	1,3	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1	10,1	10,2	11,1
Components and Features		Frame			Jamb Type	Interlock Type	Heel Type	Fly screen Type	Rubber Type	Brush Type	Glass Type	Wheels Type	Handle		Brackets Type
		Type	Profile Length	Coating Color									Type	Coating Color	
	MOC	MOC1	MOC2	MOC3	MOC4	MOC5	MOC6	MOC7	MOC8	MOC9	MOC10	MOC11	MOC12	MOC13	MOC14
MOC dollar contribution per yearly overhead cost areas	Additional Cost of Operation	3	3	1	3	3	3	3	2	1	1	1	3	1	1
	Additional Component Inventory (holding cost)	5	0	3	5	5	5	5	4	4	4	4	3	3	4
	Running Cost of New Machinery and Tooling	3	2	0	3	3	3	3	0	0	1	1	2	0	0
	Cost of additional/more skilled staff/management	3	3	2	3	3	3	3	1	1	2	1	2	2	2
	Increased Cost of Quality Control	3	4	3	3	3	3	3	1	1	3	2	2	3	2
	Increased Cost of Maintainability	1	1	1	1	1	1	1	1	1	2	0	2	1	0
	Induced Complexity Management	2	3	2	2	2	2	2	3	3	2	1	2	2	2
Overall overhead costs per unit MOC		2.86	2.29	1.71	2.86	2.86	2.86	2.86	1.71	1.57	2.14	1.43	2.29	1.71	1.57

Rating Per unit MOC	MOC dollar contributions per yearly overhead area
0	No dollar contribution needed per yearly overhead area
1	Very low dollar contribution per yearly overhead area
2	Low dollar contribution per yearly overhead area
3	Significant dollar contribution per yearly overhead area
4	High dollar contribution per yearly overhead area
5	Very high dollar contribution per yearly overhead area

In the case of aluminum windows and doors, increasing the types of extrusion profiles would entail supplementary investment costs in tooling, which is part of the infrastructural investment, seen in Section 4.6.3. Since the extrusion tools are typically kept and maintained at the aluminum extrusion plants there is no significant maintenance expense per additional extrusion tool. Therefore, the row "Increased Cost of Maintenance" has mostly values of "1" (on a scale of 0 to 5) for aluminum extrusion profiles such as the frame type, jamb type, interlock type, heel type, and fly screen type. However, new extrusion profile types would render higher inventory holding cost since a minimum level of inventory is needed for each type of additional extrusion profile. Therefore, in the row "Additional Inventory Cost" of Table 4.6, values of "5"

were estimated for the extrusions. On the other hand, increasing the increments of the cutting length for extrusions would probably require automated saws. Such saws would create significant increase in operational and maintenance expenses.

The latter row of Table 4.6 shows the overall dollar contribution of yearly operational expenses per unit MOC for each component or features, which is also accounted for on a scale of 0 to 5. Those values are expressed by Equation 4.8, where h is the total number of different areas of yearly expenses considered and R_{ij} is an indicator of the amount of operational expense allocation per unit MOC of each component "i" or feature "j" within each component. The values at the bottom of the table will serve as the coefficients for the left hand side of the *Yearly Operational Costs* goal expression. The right hand side is the upper target for yearly operational expenses allowed by the management for MC. This target is set as a percentage of the maximum operational spending level allowed by the table. The maximum operational spending level can be expressed as the sum of coefficients for each MOC multiplied by (15), which is the MOC_{max} value assigned to each component and feature in this case study.

$$\frac{1}{h}\sum_{k=1}^{h}(R_{ijk}), \text{ where } (k = 1, 2, 3 \dots h) \tag{4.8}$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(R_{ijk})\right)(MOC_{ij})\right] + d_4^- - d_4^+ = \textit{Target or Maximum Yearly Operational Cost} \tag{4.9}$$

Equation 4.9 represents the target or maximum additional yearly allowance associated to customization, which is subject to a deviation, where c is the total number of customizable components used, and f is the number of existing features per component. R_{kij} is the contribution per unit MOC of a component "i" or feature "j" to yearly operational costs. The management or

decision-makers set their target level of additional yearly allowance of the customization service. In the goal formulation (Eq. 4.9), we aim at minimizing the positive deviation (d_4^+).

4.6.5   MOC Contribution to additional Storage Area

In an MC system, component inventories tend to be higher than in a standard system, which renders increased holding cost and additional storage space requirements. The holding costs have already been accounted for as part of the yearly expenses, which was discussed in the previous sections. An example for that is Dell. To offer more potential combinations to the customer, additional versions of the same modules are required. For instance, providing more selection options for RAMs, a minimum component inventory level must be availed such as: 512 RAMs, 1024 RAMs, 2048 RAMs, 4096 RAMs. The question here is how many of each type to keep in stock? Our focus in this section is the additional storage area needed per unit MOC for each component or feature. This goal determines the maximum yearly additional space allocation that the management is willing to place for the customization service. Table 4.7 shows the space contribution per unit MOC for each component or feature to each type of storage compartment on a scale of 0 to 5.

The following are space requirements for different types of components or features:

1. Additional space requirement for extrusions.
2. Additional space requirement for accessories.
3. Additional space requirement for Rubber and Brush.
4. Additional space requirement for Glass.

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5. Additional space requirement for color coating.

Table 4.7 Space contribution of each unit MOC per component/features to various types of various storage compartments.

Serial Number (i,j)	1,1	1,2	1,3	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1	10,1	10,2	11,1
Components and Features	Frame			Jamb Type	Interlock Type	Heel Type	Fly screen Type	Rubber Type	Brush Type	Glass Type	Wheels Type	Handle		Brackets Type
	Type	Profile Length	Coating Color									Type	Coating Color	
MOC	MOC1	MOC2	MOC3	MOC4	MOC5	MOC6	MOC7	MOC8	MOC9	MOC10	MOC11	MOC12	MOC13	MOC14
Extrusion stock	5	0	0	5	5	5	5	0	0	0	0	0	0	0
Accessory Stock	0	0	0	0	0	0	0	0	0	0	1	2	0	1
Rubber & Brush Stock	0	0	0	0	0	0	0	2	2	0	0	0	0	0
Glass Stock	0	0	0	0	0	0	0	0	0	5	0	0	0	0
Coating Stock	0	0	1	0	0	0	0	0	0	0	0	0	1	0
Overall storage space per unit MOC	1.00	-	0.20	1.00	1.00	1.00	1.00	0.40	0.40	1.00	0.20	0.40	0.20	0.20

(MOC space contribution per storage compartment)

Rating Per unit MOC	MOC space contributions per storage compartment
0	No contribution per storage compartment
1	Very Low contribution per storage compartment
2	Low contribution per storage compartment
3	Significant contribution per storage compartment
4	High contribution per storage compartment
5	Very high contribution per storage compartment

The bottom row of Table 4.7 shows the overall space contribution of storage space per unit MOC for each component or features, which is also accounted for on a scale of 0 to 5. Those values are expressed by Equation 4.10, where h is the total number of different areas of yearly expenses considered and S_{ij} is an indicator of the amount of operational expense allocation per unit MOC of each component "i" or feature "j" within each component. The values at the bottom of the table will serve as the coefficients for the left hand side of the *Storage Space* goal expression. The right hand side is the upper target for the storage space allocated by the management for MC. This target is set as a percentage of the maximum storage space level allowed by the table. The maximum storage space level can be expressed as the sum of coefficients for each MOC multiplied by (15), which is the MOC_{max} value assigned to each component and feature in this case study.

$$\frac{1}{h}\sum_{k=1}^{h}(S_{ijk}) \text{, where } (k = 1, 2, 3 \dots h) \tag{4.10}$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(S_{ijk}) \right)\left(MOC_{ij}\right) \right] + d_5^- - d_5^+ = \textit{Target or Maximum Storage area} \tag{4.11}$$

Equation 4.11 represents the target or maximum additional storage area allowed for customization, which is subject to a deviation, where c is the total number of customizable components used, and f is the number of existing features per component. S_{kij} is the contribution per unit MOC of a component "i" or feature "j" to the storage space. The management or decision-makers set their maximum target level of space. In the goal expression shown in Eq. 4.11, we aim at minimizing the positive deviation (d_5^+).

4.7   Applying the Goal Programming Model (Step-6)

The overall contributors per unit MOC have been listed in Table 4.8. For all customizable components or features the labels "i" and "j" have been disregarded and given a serial from 1 to 14. On the left side of Table 4.8 there is a list of the five goals that were identified and ranked. At the right side is the list of goals or targets that the management attempts to achieve. The first two goals are shaded in green. For those two goals, we would want to minimize the negative deviation. A positive deviation would not harm; it would just mean that the management undermined their capabilities and higher target values could be achieved. The next three goals are presented with a blue shade. In our formulation we would want to minimize the positive deviation. A negative deviation would not harm; it would just indicate that there is more room for savings.

Table 4.8 The overall contributions per unit MOC.

GOALS	Frame Type MOC1	Frame Profile Length MOC2	Frame Coating Color MOC3	Jamb Type MOC4	Interlock Type MOC5	Heel Type MOC6	Fly-screen Type MOC7	Rubber Type MOC8	Brush Type MOC9	Glass Type MOC10	Wheels Type MOC11	Handle Type MOC12	Handle Coating Color MOC13	Brackets Type MOC14	Type of Optimization	Goal	Units	Table values
1 Customer Satisfaction	1.90	3.90	3.60	1.90	1.90	1.90	1.90	1.20	1.00	3.95	0.65	4.00	3.60	0.80	>(max)	50.0%	Satisfaction Increase (%)	242/483
2 Market Size	2.20	3.60	3.75	2.20	2.20	2.20	2.20	2.05	2.05	4.40	1.35	3.75	3.75	2.55	>(max)	40.0%	Market Growth (%)	230/574
3 Investment Cost	2.86	1.43	1.43	2.86	2.86	2.86	2.86	2.29	2.29	1.43	1.57	1.57	1.43	1.57	<(min)	20.0%	Investment Cost (%)	88/439
4 Operational Cost	2.86	2.29	1.71	2.86	2.86	2.86	2.86	1.71	1.57	2.14	1.43	2.29	1.71	1.57	<(min)	25.0%	Operational Cost (%)	115/461
5 Storage Space	1.00	-	0.20	1.00	1.00	1.00	1.00	0.40	0.40	1.00	0.20	0.40	0.20	0.20	<(min)	60.0%	Space Provision (%)	72/120

The following are the set Goal formulations that are used by the model:

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(U_{ijk})\right)(MOC_{ij})\right]+d_1^- - d_1^+ = \underline{\mathbf{50\%}} \qquad (4.3')$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(N_{ijk})\right)(MOC_{ij})\right]+d_2^- - d_2^+ = \underline{\mathbf{40\%}} \qquad (4.5')$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(I_{ijk})\right)(MOC_{ij})\right]+d_3^- - d_3^+ = \underline{\mathbf{20\%}} \qquad (4.7')$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(R_{ijk})\right)(MOC_{ij})\right]+d_4^- - d_4^+ = \underline{\mathbf{25\%}} \qquad (4.9')$$

$$\left[\sum_{i=1}^{c}\sum_{j=1}^{f}\left(\frac{1}{h}\sum_{k=1}^{h}(S_{ijk})\right)(MOC_{ij})\right]+d_5^- - d_5^+ = \underline{\mathbf{60\%}} \qquad (4.11')$$

Objective Function:

$$\text{MIN} \quad [P_1(d_1^-) + P_2(d_2^-) - P_3(d_3^+) - P_4(d_4^+) - P_5(d_5^+)] \tag{4.12}$$

Where, $MOC_{ij}, r_{lij}, w_{kij}, d_1^-, d_2^-, d_3^+, d_4^+, d_5^+ \geq 0$

Rigid Constraints:

Eq. 4.13 represents the upper-limit constraints or MOC_{max} set by the manufacturer, which was discussed in Section 4.5 and presented in Table 4.2.

$$MOC_{ij} \leq 15, \tag{4.13}$$

where ($i = $ 1,2,3 … C), ($j = $ 1,2,3 … f) and ($MOC_{ij}, r_{lij}, w_{lij}, d_l^-, d_l^+ \geq 0$)

The above equations are used in the preemptive GP model. The Excel Solver has been employed to generate solutions and goals deviations step by step considering one goal at a time; starting from Customer Satisfactions all the way to Storage Space. The model was operated, and each step has been documented in this section. Figure 4.5 shows the initial setting and the final outcome of the model. Figure 4.6 shows the initial setting before solving the first objective function.

Table 1 (before operating)

	MOC 1 (Frame Type)	MOC 2 (Frame Profile Length)	MOC 3 (Frame Coating Color)	MOC 4 (Jamb Type)	MOC 5 (Interlock Type)	MOC 6 (Heel Type)	MOC 7 (Fly-screen Type)	MOC 8 (Rubber Type)	MOC 9 (Brush Type)	MOC 10 (Glass Type)	MOC 11 (Wheel Type)	MOC 12 (Handle Type)	MOC 13 (Handle Coating Color)	MOC 14 (Bracket Type)	d1-	d2-	d3+	d4+	d5+	=	R.H.S.	Goals	Units	Goals (%)
Objective Function (Z):	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0			
1 Customer Satisfaction	1.90	3.90	3.60	1.90	1.90	1.90	1.90	1.20	1.00	3.95	0.65	4.00	3.60	0.80	1	0	0	0	0	>=	0.00	241.50	Satisfaction Units	50.0%
2 Market Size	2.20	3.60	3.75	2.20	2.20	2.20	2.20	2.05	2.05	4.40	1.35	3.75	3.75	2.55	0	1	0	0	0	>=	0.00	229.50	Growth	40.0%
3 Investment Cost	2.86	1.43	1.43	2.86	2.86	2.86	2.86	2.29	2.29	1.43	1.57	1.57	1.43	1.57	0	0	-1	0	0	<=	0.00	87.86	Cost	20.0%
4 Running Cost	2.86	2.29	1.71	2.86	2.86	2.86	2.86	1.71	1.57	2.14	1.43	2.29	1.71	1.57	0	0	0	-1	0	<=	0.00	115.18	Cost	25.0%
5 Storage Space	1.00	-	0.20	1.00	1.00	1.00	1.00	0.40	0.40	1.00	0.20	0.40	0.20	0.20	0	0	0	0	-1	<=	0.00	72.00	Storage	60.0%
Solutions:																								
Percent Deviations															0.0%	0.0%	0.0%	0.0%	0.0%					

Table 2 (after operating)

	MOC 1 (Frame Type)	MOC 2 (Frame Profile Length)	MOC 3 (Frame Coating Color)	MOC 4 (Jamb Type)	MOC 5 (Interlock Type)	MOC 6 (Heel Type)	MOC 7 (Fly-screen Type)	MOC 8 (Rubber Type)	MOC 9 (Brush Type)	MOC 10 (Glass Type)	MOC 11 (Wheel Type)	MOC 12 (Handle Type)	MOC 13 (Handle Coating Color)	MOC 14 (Bracket Type)	d1-	d2-	d3+	d4+	d5+	=	R.H.S.	Goals	Units	Goals (%)
Objective Function (Z):	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	=	0			
1 Customer Satisfaction	1.90	3.90	3.60	1.90	1.90	1.90	1.90	1.20	1.00	3.95	0.65	4.00	3.60	0.80	0	0	0	0	0	>=	255.44	241.50	Satisfaction Units	50.0%
2 Market Size	2.20	3.60	3.75	2.20	2.20	2.20	2.20	2.05	2.05	4.40	1.35	3.75	3.75	2.55	0	0	0	0	0	>=	266.86	229.50	Growth	40.0%
3 Investment Cost	2.86	1.43	1.43	2.86	2.86	2.86	2.86	2.29	2.29	1.43	1.57	1.57	1.43	1.57	0	0	0	0	0	<=	114.21	108.51	Cost	24.7%
4 Running Cost	2.86	2.29	1.71	2.86	2.86	2.86	2.86	1.71	1.57	2.14	1.43	2.29	1.71	1.57	0	0	0	0	0	<=	148.01	145.38	Cost	31.6%
5 Storage Space	1.00	-	0.20	1.00	1.00	1.00	1.00	0.40	0.40	1.00	0.20	0.40	0.20	0.20	0	0	0	0	-1	<=	28.92	72.00	Storage	60.0%
Solutions:	1.00	15.00	14.62	1.00	1.00	1.00	1.00	1.00	1.00	15.00	1.00	4.48	15.00	1.00	0	0	0	0	0					
Percent Deviations															0.0%	0.0%	0.0%	0.0%	0.0%					

Figure 4.5 The entire model setting before and after operating it.

	Goals	Deviation (1)	Deviation (2)	Deviation (3)	Deviation (4)	Deviation (5)		SOLUTION
Objective Function (Z):		0	0	0	0	0	=	0

	Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
1	Customer Satisfaction	1	0	0	0	0	>=	0.00	241.50	Satisfaction Units	50.0%
2	Market Size	0	1	0	0	0	>=	0.00	229.50	Growth	40.0%
3	Investment Cost	0	0	-1	0	0	<=	0.00	87.86	Cost	20.0%
4	Running Cost	0	0	0	-1	0	<=	0.00	115.18	Cost	25.0%
5	Storage Space	0	0	0	0	-1	<=	0.00	72.00	Storage	60.0%

Solutions:					
	0.0%	0.0%	0.0%	0.0%	0.0%	**Percent Deviations**

Figure 4.6 The initial model setting before operating it.

| Objective Function (Z): | 1 | 0 | 0 | 0 | 0 | = | 0 | | | |

	Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
1	Customer Satisfaction	1	0	0	0	0	>=	241.50	241.50	Satisfaction Units	50.0%
2	Market Size	0	1	0	0	0	>=	243.96	229.50	Growth	40.0%
3	Investment Cost	0	0	-1	0	0	<=	110.45	87.86	Cost	20.0%
4	Running Cost	0	0	0	-1	0	<=	141.71	115.18	Cost	25.0%
5	Storage Space	0	0	0	0	-1	<=	19.08	72.00	Storage	60.0%

Solutions:	0	0	0	0	0
	0.0%	0.0%	0.0%	0.0%	0.0%	Percent Deviations

Figure 4.7 Solving for the first goal – customer satisfaction.

The model was operated for the first goal, with an objective to minimize the negative deviation for customer satisfaction (Figure 4.7). The first goal was met, which means that at this stage, the targeted satisfaction level of 50% or (241.5/483) was met without any deviations. Now we can convert this goal to a rigid constraint (in the negative direction) and solve for the second goal.

	Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
	Objective Function (Z):	0	1	0	0	0	=	0			
1	Customer Satisfaction	0	0	0	0	0	>=	241.50	241.50	Satisfaction Units	50.0%
2	Market Size	0	1	0	0	0	>=	253.79	229.50	Growth	40.0%
3	Investment Cost	0	0	-1	0	0	<=	108.73	87.86	Cost	20.0%
4	Running Cost	0	0	0	-1	0	<=	140.05	115.18	Cost	25.0%
5	Storage Space	0	0	0	0	-1	<=	27.52	72.00	Storage	60.0%

Solutions:	0	0	0	0	0
	0.0%	0.0%	0.0%	0.0%	0.0%	Percent Deviations
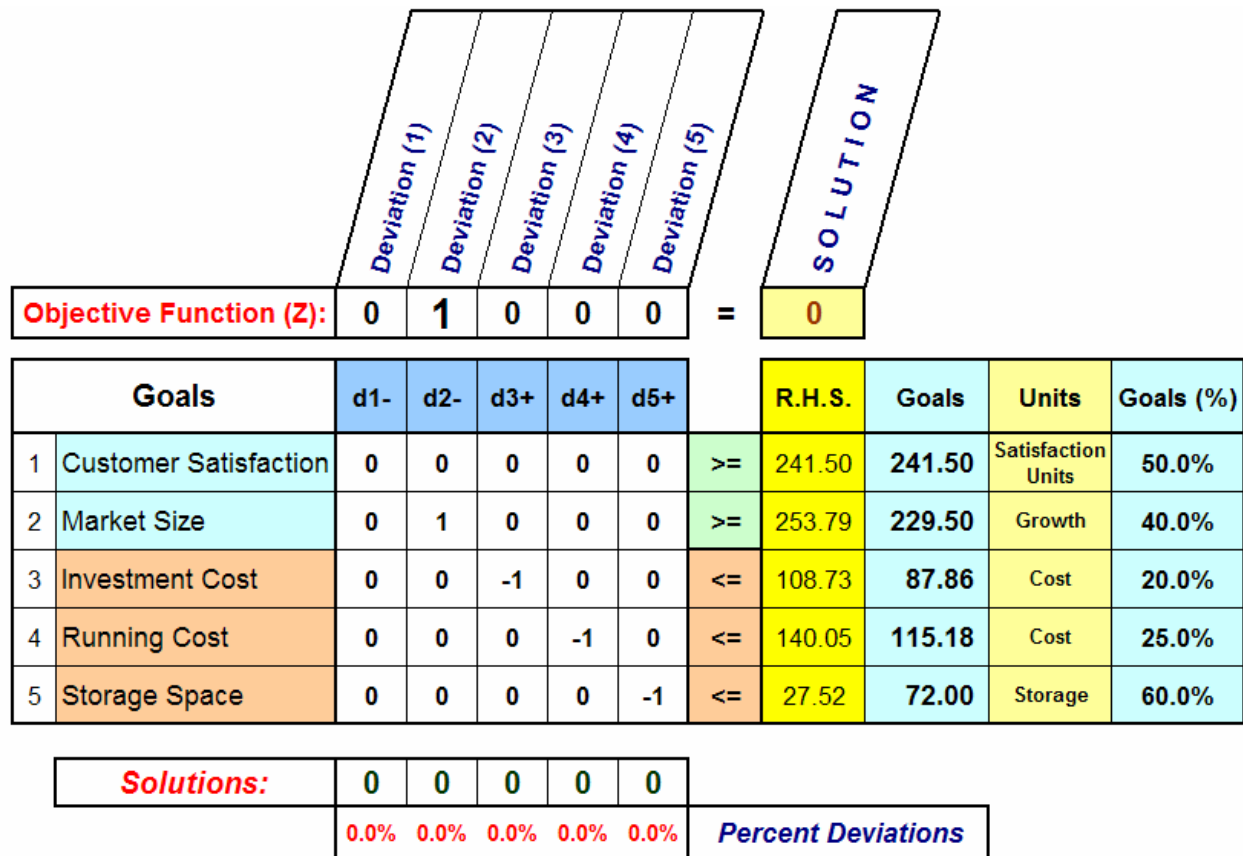
Figure 4.8 Solving for the second goal – market size.

The model was operated for the second goal, with an objective to minimize the negative deviation for the market growth targeted (Figure 4.8). The second goal was met, which means that at this stage, the targeted market growth of 40% or (229.5/574) was achieved without any deviations. Now we can convert this goal to a fixed constraint (in the negative direction) and move to the next goal. At this point the successive goals are forced to respect the initial goals with possible deviations.

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| Objective Function (Z): | 0 | 0 | 1 | 0 | 0 | = | 20.65 | | | |

	Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
1	Customer Satisfaction	0	0	0	0	0	>=	241.50	241.50	Satisfaction Units	50.0%
2	Market Size	0	0	0	0	0	>=	247.96	229.50	Growth	40.0%
3	Investment Cost	0	0	-1	0	0	<=	87.86	87.86	Cost	20.0%
4	Running Cost	0	0	0	-1	0	<=	145.38	115.18	Cost	25.0%
5	Storage Space	0	0	0	0	-1	<=	30.01	72.00	Storage	60.0%

Solutions:	0	0	21	0	0
	0.0%	0.0%	4.7%	0.0%	0.0%	Percent Deviations

Figure 4.9 Solving for the third goal – investment cost.

The model was operated for the third goal with an objective to minimize the positive deviation for the investment costs for customization (Figure 4.9). The goal of 20% or (88/439) was met but at minimum positive deviation of 4.7%. This means that to respect the first two goals at least 24.7% worth of additional investment is needed. The deviation was accepted and the investment was modified to a fixed constraint at 24.7% (in the negative direction). At this point the successive goals are forced to respect the initial goals with their updated deviation settings.

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Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
Objective Function (Z):	0	0	0	0	0	=	0			
1 Customer Satisfaction	1	0	0	0	0	>=	0.00	241.50	Satisfaction Units	50.0%
2 Market Size	0	1	0	0	0	>=	0.00	229.50	Growth	40.0%
3 Investment Cost	0	0	-1	0	0	<=	0.00	87.86	Cost	20.0%
4 Running Cost	0	0	0	-1	0	<=	0.00	115.18	Cost	25.0%
5 Storage Space	0	0	0	0	-1	<=	0.00	72.00	Storage	60.0%
Solutions:										
	0.0%	0.0%	0.0%	0.0%	0.0%	**Percent Deviations**				
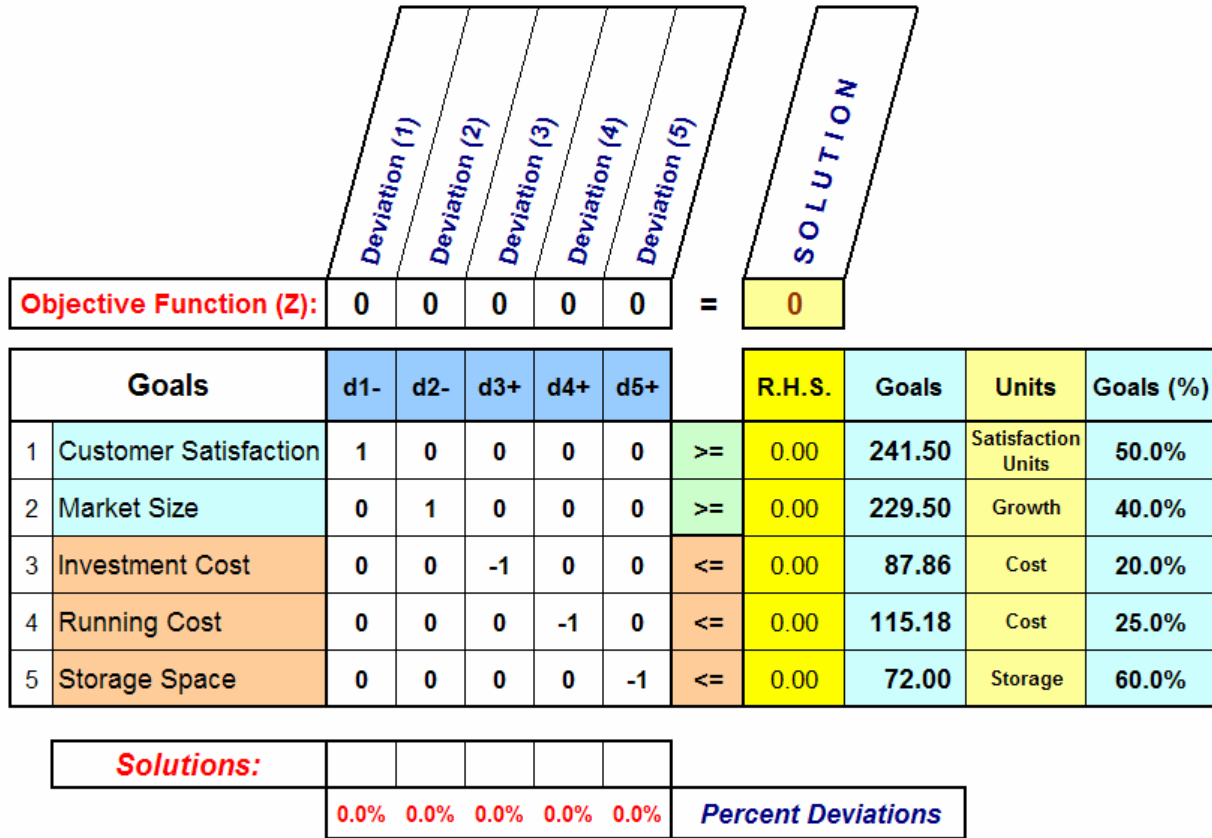
Figure 4.10 Solving for the fourth goal – running cost.

The model was operated for the fourth goal with an objective to minimize the positive deviation for the yearly operational costs for customization (Figure 4.10). The goal of 25% or (115/461) was met but with a minimum positive deviation of 6.6%. This means that to respect the first three goals, 31.6% worth of additional yearly operational cost is required. This deviation was also accepted and the yearly operational cost function was modified to a fixed constraint at 31.6% (in the negative direction). At this point the successive goals are forced to respect the initial goals with their updated deviation settings.

Goals	d1-	d2-	d3+	d4+	d5+		R.H.S.	Goals	Units	Goals (%)
Objective Function (Z):	0	0	0	0	1	=	0			
1 Customer Satisfaction	0	0	0	0	0	>=	255.44	241.50	Satisfaction Units	50.0%
2 Market Size	0	0	0	0	0	>=	266.86	229.50	Growth	40.0%
3 Investment Cost	0	0	0	0	0	<=	114.21	108.51	Cost	24.7%
4 Running Cost	0	0	0	0	0	<=	148.01	145.38	Cost	31.6%
5 Storage Space	0	0	0	0	-1	<=	28.92	72.00	Storage	60.0%
Solutions:	0	0	0	0	0					
	0.0%	0.0%	0.0%	0.0%	0.0%		**Percent Deviations**			
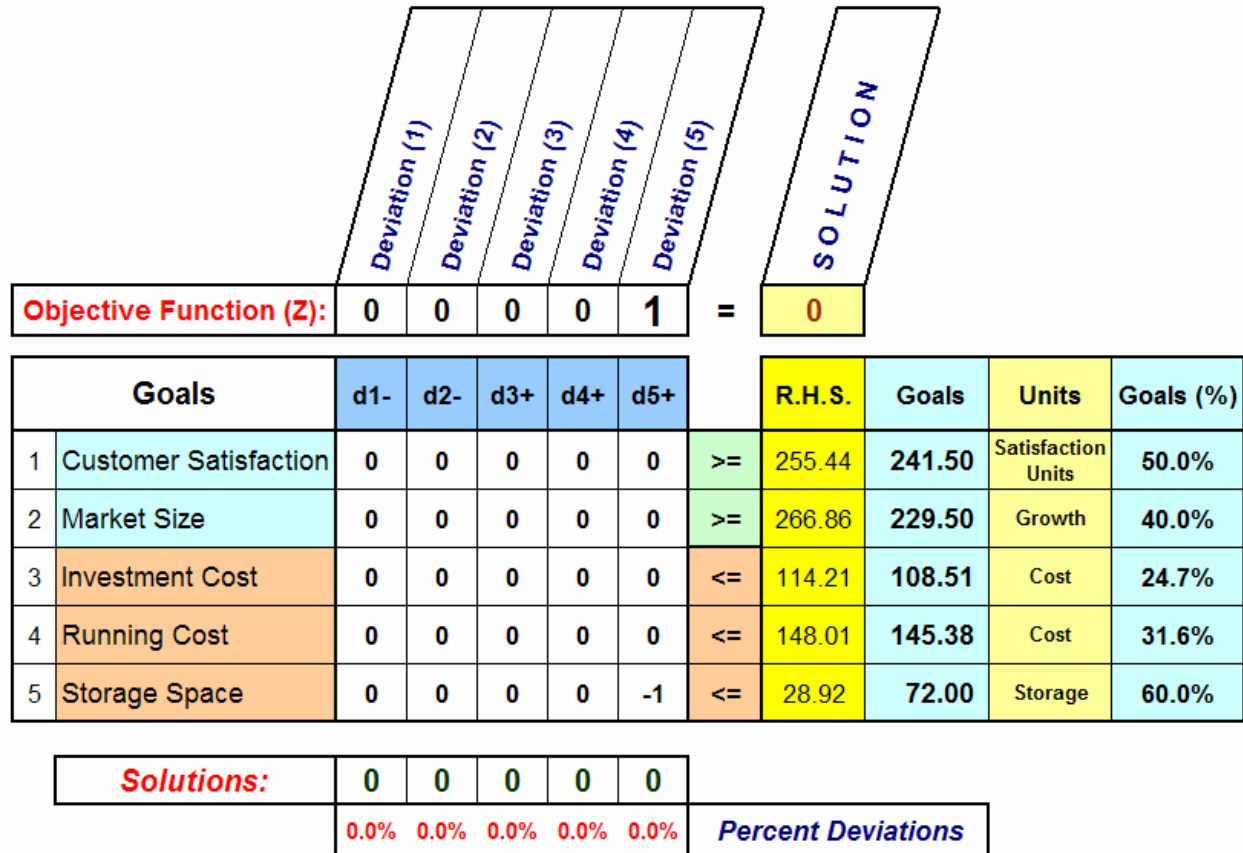
Figure 4.11 Solving for the fifth goal – storage area.

The model was operated for the fifth and last goal with an objective to minimize the positive deviation for the additional storage area for customization (Figure 4.11). The goal was met with no deviations. At this stage the model operation is complete and we can view the MOC corresponding solutions.

The presence of some deviations shows that the initial goals settings were narrow and the MOC solution will barely realize those goals. However, if there are no deviations throughout the model operation, this could indicate that the management underestimated their capability and resources potentials and they can aim for higher or more competitive goals settings. This can be dealt with by performing the sensitivity analysis which is shown in Appendix A. Later, the

model can be operated another time with possibly a higher level of satisfaction or higher

percentage of Market growth as targets. By monitoring the corresponding deviations, it is up to

the management to decide when to draw the line.

The final MOC solutions for all the components or features are illustrated in Figure 4.5 at

the right side. The management can assess the deviations and examine the sensitivity analysis to

see if any changes to the targets are needed. If changes to the targets are made, the new settings

are introduced and model is operated one more time. This process can be repeated until the level

of deviations is satisfactory.

4.8   Converting the Model Solutions to Meaningful Values

4.8.1   Model Outcome for Production Planning (Step-7)

Once the final solutions have been obtained we move to Step-7 of the model algorithm,

which is to convert the MOC results to meaningful values that can be used for production

planning. We use the expressions developed in Section 4.5 and shown in Table 4.2. The outcome

has been rounded to the nearest integer and translated to meaningful recommendations as seen in

Table 4.9.

Table 4.9 Converting the model outcome meaningful values

MOC #	Components and Features		Serial (i,j)	MOC Solution	Results
1	Frame	Type	1,1	1.00	One type of frame extrusion profile
2		Profile Length	1,2	15.00	Custom frame size
3		Coating Color	1,3	14.62	Spectrum of coating colors offered
4	Jamb Type		2,1	1.00	One type of jamb extrusion profile
5	Interlock Type		3,1	1.00	One type of interlock extrusion profile
6	Heel Type		4,1	1.00	One type of heel extrusion profile
7	Fly-screen Type		5,1	1.00	One type of fly-screen extrusion profile
8	Rubber Type		6,1	1.00	One type of rubber
9	Brush Type		7,1	1.00	One type of brush
10	Glass Type		8,1	15.00	Any glass type available in the market
11	Wheels Type		9,1	1.00	One type of wheel
12	Handle	Type	10,1	4.48	40 handles
13		Coating Color	10,2	15.00	Spectrum of coating colors offered
14	Brackets Type		11,1	1.00	One type of bracket

The results indicate that only one type for all extrusions should be enough to avail as far as customization is concerned. As for the cut length increments, the model indicated that a custom cut would be the best solution, rather than having a set of fixed sizes. The coating color for the extrusions as well as for the handles had similar outcomes; the solutions indicated that a

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spectrum of color should be availed for both. However, the number of handles that need to be offered was limited to 40 types. The glass also had an open choice solution that is confined to whatever is available in the market. Therefore, the manufacturer may need to have more than one glass supplier to cover all different types of glass. The rest of the components all had a single choice solution, which was excepted since they did not have a significant impact on customer satisfaction or market growth. However, increasing their scope of options would have rendered higher costs. It is recommended to standardize such components and features.

4.8.2   Computing the GMOC for Upper Management (Step-8)

In Step-8, which is the final step in the model algorithm, we combine the MOC solutions to get an overall figure for the degree of customization of the product in the system. That is obtained by computing the Global MOC (GMOC) as shown in Table 4.10. The GMOC value is then converted to a degree of customization (C_z) by using Eq. 3.3.

Table 4.10 Computations for the GMOC and overall degree of customization.

Components	MOC for Feature-1 (DOF-1)	Description	MOC for Feature-2 (DOF-2)	Description	MOC for Feature-3 (DOF-3)	Description	Total (MOC)
Frame	1	Type	15	(W x L)	15	Coating	225
Jamb	1	Type	1	(W x L)	1	Coating	1
Interlock	1	Type	1	(W x L)	1	Coating	1
Heel	1	Type	1	(W x L)	1	Coating	1
Flyscreen	1	Type	1	(W x L)	1	Coating	1
Rubber	1	Type	1	(W x L)	1	none	1
Brush	1	Type	1	(W x L)	1	none	1
Glass	15	Type	1	(W x L)	1	none	15
Wheels	1	Type	1	none	1	none	1
Handle	4	Type	1	none	15	Coating	60
Brackets	1	Type	1	none	1	none	1
Global Magnitude of Customization (GMOC) …							202,500

$$C_z = \frac{Log(GMOC)}{Log(GMOC_{max})} \qquad\qquad (3.3')$$

$$C_z = \frac{Log(202{,}500)}{Log(2.9192\text{x}10^{16})} = 0.3223 \quad \text{or} \quad 32.23\% \qquad\qquad (4.14)$$

A degree of customization of 32.23% is not a value of much significance on its own. However, it will become meaningful when benchmarked to double panel sliding windows for other aluminum windows and doors companies.

4.9 Further Analysis and Evaluation:

4.9.1 Verification of the Modeling Approach

The verification process deals with proving that the model is functional and that it gives results that are reflective of the input parameters. To verify the model there needs to be a good understanding of the model's dynamics. For example, in our case of double panel sliding window, five goals have been identified. From such goals two optimistic goals and three restrictive goals were determined. The first two goals tend to maximize the customization level since increasing satisfaction and market size are directly proportional to customization. On the other hand, the latter three goals tend to pull the customization level down. That is, to comply with the maximum setting for investment costs, operational costs, and storage area, customization needs to be reduced to a certain limit. Those opposing objectives tend to push and pull the level of customization finally creating the balance upon which the MOC solutions are extracted. To verify the model a test was performed by increasing the costs or storage

contributions per unit MOC and/or reducing the contribution per unit MOC for satisfaction and market share. As expected the results yielded an overall lower set of MOC values. The same test was performed, but in a reverse fashion. We reduced the cost or storage contributions and/or increased the targets for satisfaction and market growth. The results yielded a generally higher set of MOC values. This effect can also be detected by analyzing the sensitivity analysis report shown in Appendix A. Those tests were performed and the results turned out as expected which proves that the model is functional and that it is structurally and mathematically correct.

4.9.2   Validation of the Modeling Approach

The validation process is about proving the purpose of the model and whether it meets the reason for which is was constructed. In our case, we need to know whether the model outcome was useful to the decision-maker and whether it helped the company better meet their organizational strategic goals. It is challenging to validate the usefulness of the model as it would entail having to wait for the company to actually fulfill their strategic goals and prosper on the long run and then try to map this to the implementation of customization based on the MOC solutions.

A more direct approach for verifying the model outcome is to map it to manufacturer's current customization status or nonbiased recommendations for what the best level of customization should be. We assume that the manufacture is experienced, has been in business for years and should by now, through trial and error, have achieved a reasonable or convenient level of customization. In addition, we consider a double panel sliding window a relatively simple product that has a limited number of customizable components and features. So, it would be uncomplicated for the management to reach a customization level that has a relatively good

contribution to their organizational goals, without the use of sophisticated tools. On the other hand, in other cases of more complex products that include numerous components and/or features and more organizational goals to keep in mind, reaching a best customization level may be challenging. In such a case, a scientific tool, such as the model we are offering, would become handy.

To validate the model the management has been asked, as a final question in the survey, to specify their current or recommended level of customization for each component and feature that has been listed. For details, refer to Question 6 of the survey in Appendix B. This question was answered without, the management, having prior knowledge or indications about the model results. The management answers were later converted to MOC values and compared to the model results as shown in Figure 4.11.

Table 4.11 Comparing the model MOC results with the actual or recommend company status.

MOC #	Components and Features		MOC Solution	Model Results	MOC Actual	Current Company Status	Differece
1	Frame	Type	1.00	One type of frame extrusion profile	2.00	2 types of frame extrusion profiles	7.1%
2		Profile Length	15.00	Custom frame size	15.00	Custom frame size	0.0%
3		Coating Color	14.62	Spectrum of coating colors offered	15.00	Spectrum of coating colors offered	2.7%
4	Jamb Type		1.00	One type of jamb extrusion profile	2.00	2 types of jamb extrusion profiles	7.1%
5	Interlock Type		1.00	One type of interlock extrusion profile	2.00	2 types of interlock extrusion profiles	7.1%
6	Heel Type		1.00	One type of heel extrusion profile	2.00	2 types of heel extrusion profiles	7.1%
7	Fly-screen Type		1.00	One type of fly-screen extrusion profile	2.00	2 types of fly-screen extrusion profiles	7.1%
8	Rubber Type		1.00	One type of rubber	1.00	One type of rubber	0.0%
9	Brush Type		1.00	One type of brush	1.00	One type of brush	0.0%
10	Glass Type		15.00	Any glass type available in the market	15.00	Any glass type available in the market	0.0%
11	Wheels Type		1.00	One type of wheel	3.00	3 types of wheels	14.3%
12	Handle	Type	4.48	40 handles	2.00	20 handles	17.7%
13		Coating Color	15.00	Spectrum of coating colors offered	15.00	Spectrum of coating colors offered	0.0%
14	Brackets Type		1.00	One type of bracket	3.00	3 types of brackets	14.3%
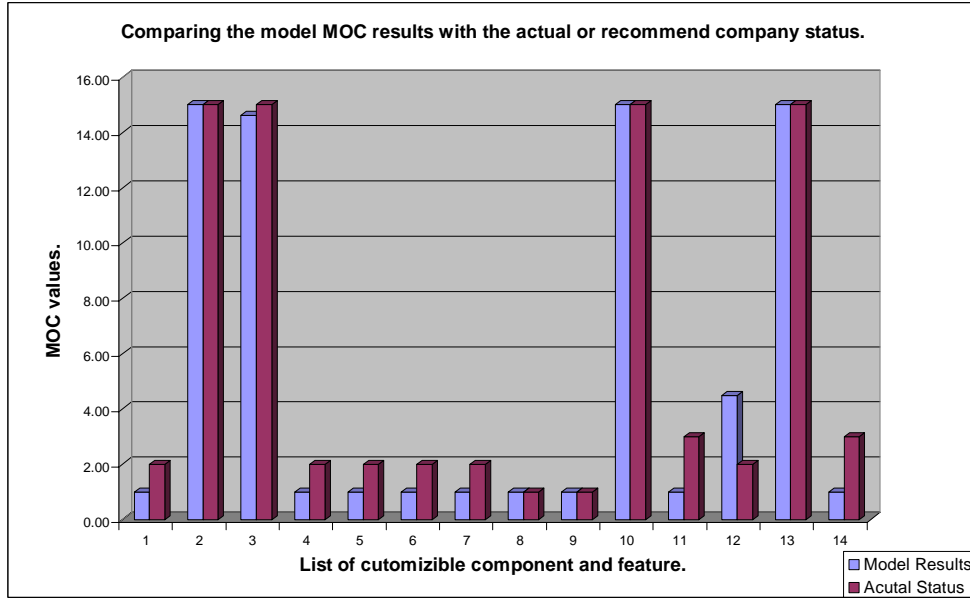
Figure 4.12 Comparing the model MOC results with the actual or recommend company status.

The percentage difference between the actual or recommended MOC values and the model MOC results are computed by using Eq. 4.15, where, MOC_{max} is the upper-limit MOC defined by the conversion expressions in Table 4.2.

$$\text{Percentage Difference} = \left| \frac{(MOC_{Actual}) - (MOC_{Model})}{MOC_{max}} \right| \cdot (100) \qquad (4.15)$$

The average percentage difference between the model MOC results and the actual or recommended status is approximately 6.05% at a standard deviation of 6.02% and variance of 36.29%. We can also notice from Figure 4.12 that there was no major difference in results for any of the 14 components and features. The highest difference was for the *Handle Type,* which was around 17.7%. The management may, in fact, consider increasing the number of handle types provided in the future; however, they affirmed that this number is satisfactory for the time being.

Further more, the model outcome is reasonably close to our expectations. That is, components or features that, if customized, have a large impact on customer satisfaction or market growth and that do not render relatively significant costs of customization would be good candidates for maximizing the degree of customization, and vice versa. This logic was reflected throughout model results.

The purpose of this case study was to validate the proposed model and techniques developed, by showing that they are, in fact, functional and useful as a decision-making tools for mass customizers.

CHAPTER 5: MODEL DISCUSSION AND FURTHER RESEARCH AREAS

5.1 Means of Improving the Expression for MOC Contributions

The unit MOC contributions to the goals, developed in Section 4.6, were subjective estimates made by the management including the Marketing Finance and Operations department. Suggestions are made as to how the model can be improved and the formulations more refined. Sections 5.1.1 and 5.1.2 show examples of methods for further analyzing the MOC contribution to Customer satisfaction and Operational Expenses.

5.1.1 Methods to Improve Estimation of MOC Contribution to Customer Satisfaction

There are several well researched techniques that aim at better understanding the customer and relating that to product characteristics. Those methods can be further developed to link the customer experience to the degree of customization.

For example, the User-Centered Design (UCD) is a design approach, combining various fields of study that are based on the active involvement of users, their requirements and expectations in order to improve the understanding of the user and the task, as well as the iteration of design and evaluation (Vredenburg *et al.*, 2002). UCD is typically used to obtain the product attributes based on market research and a thorough understanding of customers' needs, requirements and expectations. As has been seen in our case study (Chapter 4), increasing customer satisfaction was considered a goal of high priority. We suggest expanding upon this

goal by incorporating UCD criteria in order to generate an enhanced solution for the degree of customization. In this process we propose to relate the MOC contributors of each component and feature to relevant UCD criteria. This method may include multidisciplinary design teams, task analysis, competitive evaluation, design walkthrough, iterative design evaluation, and benchmarking among other assessments. Previous studies (Meza, 2006) have identified specific UCD attributes in the form of components and their factors that should be taken into consideration when designing a product.

Another approach is "Kansei engineering" which is "an ergonomic technology of consumer oriented product development. It focuses not on the manufacturer's intention but rather on the customer's feelings and needs" (Nagamachi, 1995). For years, Kansei has been used as a powerful tool for product development to help design Japanese cars and their interior (Nagamachi, 2002). Porcar et al., (2001) utilized the Kansei and UCD approaches to include consumer expectations into personalization.

The nature of customer satisfaction is typically in a diminishing form (Figure 5.1). The customer is very appreciative when a transformation from a single fit system to a customization service is introduced, even if only a few options are availed. However, as the number of options and scope of customization increases, the customer is less excited about the change, to a point where he/she becomes indifferent. We call that, in Figure 5.1, the indifference zone. For example, shifting from having one standard color for a car to a five color choice will significantly attract consumer's attention. Having a choice of 20 instead of five is even better; however, having 150 instead of 120 color choices starts to be unnoticeable. From a market standpoint that's what we refer to as the indifference zone. It has been discussed by many scholars in MC, that there is a level, beyond that, where the satisfaction will actually decrease,

which is refer to as "customer confusion" (Huffman *et al.*, 1998; Piller, 2006). We call it, in

Figure 5.1, the confusion zone. In our formulation we only addressed the former portion of the

curve which is up to the indifference zone, after that we asked the decision-maker to set an

MOC_{max} value (upper-limit MOC), which is the technical barrier. For example, in Section 4.5

when we addressed the number of cut increments for the extrusion profiles, the manufacture

excluded the option of having more than 15 cuts. They affirmed that beyond 15 cut increments it

is better to shift to a custom cut system.
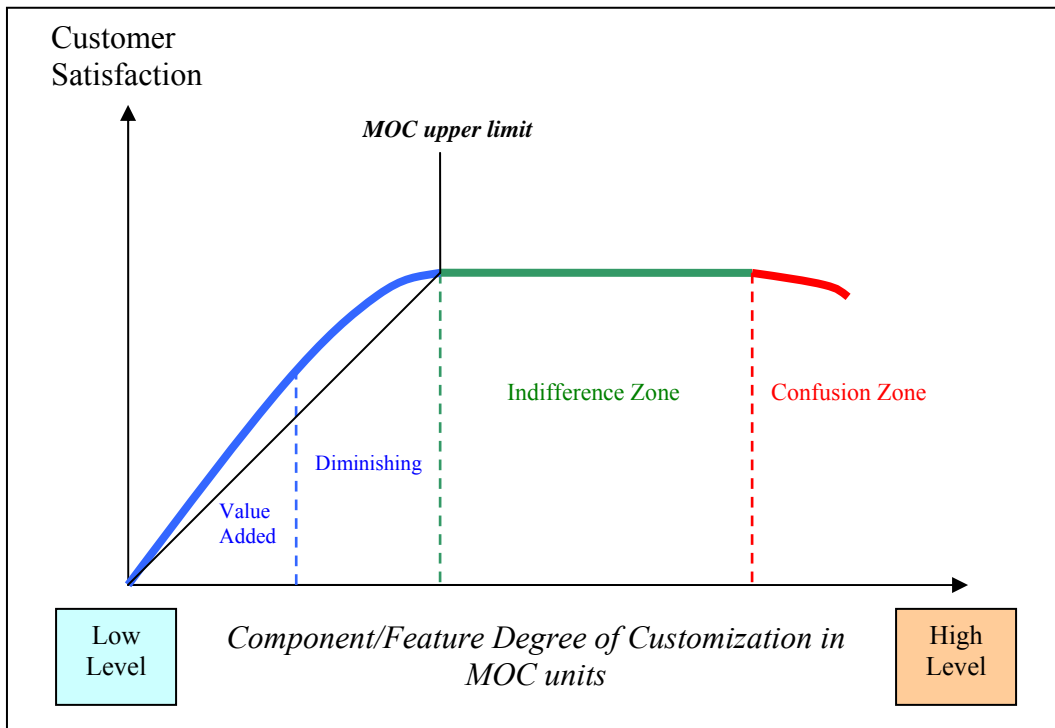
Figure 5.1 The MOC contribution to customer satisfaction.

5.1.2   Analysis of the MOC Contribution to Operational Cost

The operational cost curve versus the MOC typically depends on the process and

technology being applied. A single fit system technology is expected to render high costs upon

increasing the MOC level. This is seen by the steep slope of the initial portion of the curve in

Figure 5.2. Therefore, after a certain level of customization the management decides to adopt a

new technology that would be less costly for component/feature variation. That is captured by

the second portion on the curve having a less steep slop. Finally, the best technology for an MC

system would be one that has a cost that is independent of component or feature customization.

An example for that would be the additive fabrication or rapid manufacturing technology. In our

case study in Chapter 4, for simplicity, we only addressed the initial portion of the curve.

However, there is room for expanding the formulation to include a more exact function or even a

step functions as show in Figure 5.2.
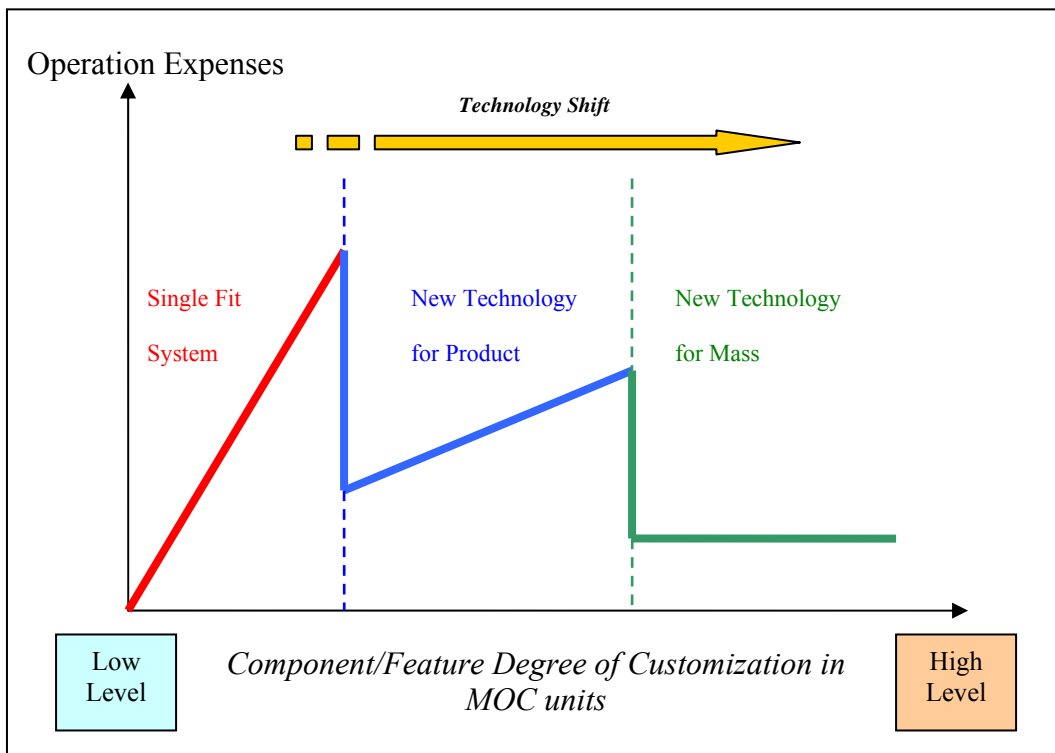
Figure 5.2 The MOC contribution to yearly running costs.

In the present case, we have demonstrated a technique to compute the overall degree of customization for an aluminum windows and doors company, by using a double panel sliding window as our test vehicle. The reason for choosing this particular product was because it constitutes 80% of the sales. However, there are other popular products that are being offered such as: hinges windows, pivot windows, tilt windows, tilt-slide windows, fold doors and others. The double panel sliding window alone may not be representative of the overall level or targeted level of customization for the company. One suggestion for that is to operate a modified model that includes each and every category of products having normalized weights based on sales volume or the popularity of items. Equation 5.1 shows the updated goal expression including multiple products, where S_m is the normalized weight of every product m, and G is the total number of products in the system. The rest of the annotations for Equations 3.1' and 5.1 are identical to the ones developed and discussed in Section 3.5.

Objective function:

$$\text{MIN} \sum_{l=1}^{N} P_l\left((-d_l^+)or(+d_l^-)\right) \tag{3.12'}$$

New Goals:

$$\sum_{q=1}^{G} S_m \left(\sum_{i=1}^{c}\sum_{j=1}^{f} F_{lqij}(r_{lqij}, w_{lqij})MOC_{qij} \right) + d_l^- - d_l^+ = Goal(l) \tag{5.1}$$

where $(l = 1, 2, 3 \dots N)$, $(i = 1,2,3 \dots C)$, $(j = 1,2,3 \dots f)$, $(q = 1,2,3 \dots G)$ and $(MOC_{qij}, r_{lqij}, w_{lqij}, d_l^-, d_l^+ \geq 0)$

5.3   Conclusions and Further Research

In an MC system, personalized products can have different modular choices and varying extents for customizable features. It is important to know which set of components and/or feature choices, specifically, need to be expanded or narrowed down to best help companies meet their strategic goals.

The use of the "customization scale" has been introduced as an overall indicator for the level of customization for a particular product. To determine numeric measures for the degree of customization, which we refer to as MOC units, a technique has been developed that addresses each component and feature pertaining to a product.

As an application to the MOC, an analytical optimization model has been employed that utilizes the MOC values as decision variables for a decision-making process. The model is expected to aid the investors or management, willing to venture into MC, better meet their own organizational and strategic goals. The model is not expected to provide an exact solution for the optimal level of customization. However, it should put investors or management on the right track as far as the extent of customization, regarding each component/feature of products, is concerned.

The proposed model offers the seed to a new convention that can be further expanded to provide more accurate and practical results. Each goal expression that has been developed, in Chapter 4, can be further development and refined. As an example for that, Sections 5.1.1 and 5.1.2 discussed how the goal expressions for customer satisfaction and operational costs may open doors for more research. Also the scope of this research was confined to a single category of products within a company. In Section 5.2 we showed that the goal expression can be modified to encompass multiple products.

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The advantage of preemptive goal programming, as an optimization tool, is that goals can be independent of each other as far as the units of measure and number of goals are concerned. This provides the required flexibility to adapt this technique to different industries and categories of products. However, one of the limitations of preemptive goal programming is that the solution obtained by solving the first goal might have a dominant effect on the next goal and the other goals to follow. The latter goals on the priority list might become immaterial if the former goals are too restrictive. Therefore, it is imperative that the prioritization be performed with extreme care. The purposed model presents a frame work that combines various research efforts into a flexible but encompassing method that can provide decision-makers, willing to adopt MC, with essential production planning guidelines and a valuables benchmarking tool.

Before coming up with a commercial package that is based on the MOC philosophy, extensive research needs to be conducted in various areas to attain more accurate expressions for the goals. Also this package needs to be customizable, to fit different disciplines and applications.

APPENDIX A: SENSITIVITY ANALYSYS

Adjustable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
D12	Solutions: MOC 1	1.00	0.00	0	1E+30	0
E12	Solutions: MOC 2	15.00	0.00	0	0	1E+30
F12	Solutions: MOC 3	14.62	0.00	0	0	1E+30
G12	Solutions: MOC 4	1.00	0.00	0	1E+30	0
H12	Solutions: MOC 5	1.00	0.00	0	1E+30	0
I12	Solutions: MOC 6	1.00	0.00	0	1E+30	0
J12	Solutions: MOC 7	1.00	0.00	0	1E+30	0
K12	Solutions: MOC 8	1.00	0.00	0	1E+30	0
L12	Solutions: MOC 9	1.00	0.00	0	1E+30	0
M12	Solutions: MOC 10	15.00	0.00	0	0	1E+30
N12	Solutions: MOC 11	1.00	0.00	0	1E+30	0
O12	Solutions: MOC 12	4.48	0.00	0	1E+30	0
P12	Solutions: MOC 13	15.00	0.00	0	0	1E+30
Q12	Solutions: MOC 14	1.00	0.00	0	1E+30	0
R12	Solutions: d1-	0	0	0	1E+30	0
S12	Solutions: d2-	0	0	0	1E+30	0
T12	Solutions: d3+	0	0	0	1E+30	0
U12	Solutions: d4+	0	0	0	1E+30	0
V12	Solutions: d5+	0	1	1	1E+30	1

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
X16	< R.H.S.	1.00	0.0	15	1E+30	14
X17	< R.H.S.	15.00	0.0	15	0.206896549	0.002941178
X18	< R.H.S.	14.62	0.0	15	0.253924921	0.006274997
X19	< R.H.S.	1.00	0.0	15	1E+30	14
X20	< R.H.S.	1.00	0.0	15	1E+30	14
X21	< R.H.S.	1.00	0.0	15	1E+30	14
X22	< R.H.S.	1.00	0.0	15	1E+30	14
X23	< R.H.S.	1.00	0.0	15	1E+30	14
X24	< R.H.S.	1.00	0.0	15	1E+30	14
X25	< R.H.S.	15.00	0.0	15	0.173913041	0.002325583
X26	< R.H.S.	1.00	0.0	15	1E+30	14
X27	< R.H.S.	4.48	0.0	15	0.558249961	0.115705204
X28	< R.H.S.	15.00	0.0	15	0.29725557	0.011239873
X29	< R.H.S.	1.00	0.0	15	1E+30	14
X7	>= R.H.S.	248.13	0.00	229.5	18.625	1E+30
X6	>= R.H.S.	241.50	0.00	241.5	0.000714286	0.054545454
X8	<= R.H.S.	759.60	0.00	759.6	0.149999998	0.002083335
X9	<= R.H.S.	1016.60	0.00	1016.65	1E+30	0.050000028
X10	<= R.H.S.	149.70	0.00	360	1E+30	210.3

APPENDIX B: QUESTIONAIRE USED BY THE MANUFACTURER

Research Questionnaire on Mass Customization for WINDOOR Inc.

The purpose of this research is to determine the best level of customization for products that will mostly fulfill the company's strategic goals while considering resource limitations. During our study we will need to analyze in detail one of your popular products such as a double panel sliding window. We shall also seek an understanding of what the company's objectives are and how customization can contribute to its achievement.

<u>This study involves the following steps:</u>

1) Identification of company's organizational goals and objectives that can be better be achieved through customization of particular components or features. Such goals include may include targeting certain customer satisfaction levels, budget considerations, sales growth, risk factors, reputation, safety, ergonomic compliance, medical concerns, environmental issues, outsourcing and others.

2) Comparison of each of the goals identified with one another in an in an attempt to sort them in order of importance.

3) Analyzing a particular product – double panel sliding window/door – and identifying customizable components and features.

4) Estimating the contribution of customizing each component and features to the company's objectives determined.

5) Setting actual targets for each goal.

6) Listing the actual level or recommended level of customization by company experts for each component or feature (model validation).

The aim of this study is to reach a solution as to how far each component and feature pertaining to the product investigated needs to be customized to best fulfill the preset organizational objectives and existing technical constraints or resource limitations.

1) Identification of the company's organization strategic objectives:

In a mass customization system the stakeholders/decision makers would typically want to increase the component choices and controllable feature variation. What are the organizational strategic goals or mean objectives that would be served by customization? and what resources requirements would be considered?

Please, list some of the important organizational goals that may be better achieved through customization:

- Increased Customer Satisfaction.
- Additional market niches captured (market growth).
- Initial Investment Costs Consideration.
- Yearly Operational expense Consideration.
- Additional Component Storage Area Consideration.
- …
- …

2) Comparison of goals:

Compare each goal with other goals in terms of importance.
The rating is shown below:
1 = Equal importance
3 = Moderate importance
5 = Essential or strong importance
7 = Very strong importance
9 = Extreme importance

The numbers 2, 4, 6 and 8 are intermediate values between two adjacent judgments for when a compromise is needed.

	Criterion/Criterion Comparison	Increased Customer Satisfaction	Additional market niches captured	Investment Infrastructural Costs Consideration	Running and Operational Costs Consideration	Additional Component Storage Area Consideration			
A	Increased Customer Satisfaction	1							
B	Additional market niches captured		1						
C	Investment Infrastructural Costs Consideration			1					
D	Running and Operational Costs Consideration				1				
E	Additional Component Storage Area Consideration					1			
F							1		
G								1	
H									1

3) The subject product:

Identify customizable components and customizable features for a double panel sliding window/door. (Information may be filled in the next page)

Double Panel Sliding Window/Door

SCALE 1:3

SCALE 1:3
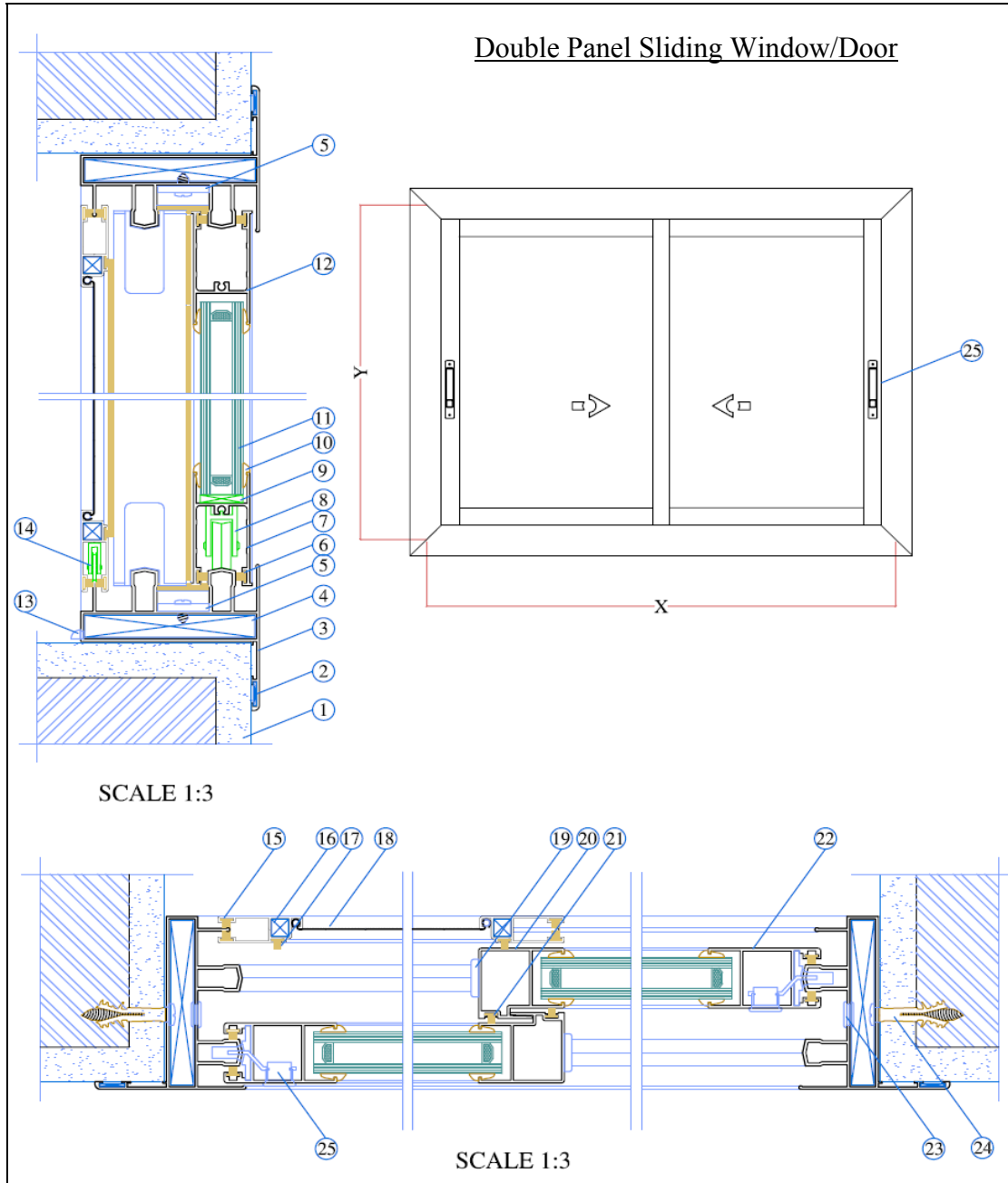
4) Contribution of each component/feature identified to the goals:

List each customizable component/feature identified in the previous question in the table below. A customer satisfaction score needs to be estimated for each component/feature on a (0-5) rating. (An example shown at the bottom of the page)

Customizable Components	Feature-1 + (Satisfaction Score)		Feature-2 + (Satisfaction Score)		Feature-3 + (Satisfaction Score)	
Frame	Type	2	Color	4	Cutting Length	4
Jamb	Type	2	Color		Cutting Length	
Interlock	Type	2	Color		Cutting Length	
Heel	Type	2	Color		Cutting Length	
Fly-screen	Type	2	Color		Cutting Length	
Rubber	Type	1				
Brush	Type	1				
Glass	Type	4				
Wheels	Type	4				
Handle	Type	3	Color	4		
Brackets	Type	1				

Rating	Contributions to different areas of customer satisfaction
0	No contribution to customer satisfaction
1	Very low contribution to customer satisfaction
2	Low contribution to customer satisfaction
3	Significant contribution to customer satisfaction
4	High contribution to customer satisfaction
5	Very high contribution to customer satisfaction

Example:

Handle	Models	5	Coating Color	3	

Estimate the percentage market growth associated with the same list of components/features in percentage or on a (0-5) rating. (Refer to rating table below)

Customizable Components	Feature-1 + (% Market Growth)		Feature-2 + (% Market Growth)		Feature-3 + (% Market Growth)	
Frame	Type		Color		Cutting Length	
Jamb	Type		Color		Cutting Length	
Interlock	Type		Color		Cutting Length	
Heel	Type		Color		Cutting Length	
Fly-screen	Type		Color		Cutting Length	
Rubber	Type					
Brush	Type					
Glass	Type					
Wheels	Type					
Handle	Type		Color			
Brackets	Type					

Rating	Contributions to sales growth
0	No contribution to sales growth
1	Very low contribution to sales growth
2	Low contribution to sales growth
3	Significant contribution to sales growth
4	High contribution to sales growth
5	Very high contribution to sales growth

Estimate the initial investment costs needed for customization that are associated with the same list of components/features in dollar values or on a (0 - 5) rating. (Refer to rating table below)

Customizable Components	Feature-1 + (Investment Costs)		Feature-2 + (Investment Costs)		Feature-3 + (Investment Costs)	
Frame	Type		Color		Cutting Length	
Jamb	Type		Color		Cutting Length	
Interlock	Type		Color		Cutting Length	
Heel	Type		Color		Cutting Length	
Fly-screen	Type		Color		Cutting Length	
Rubber	Type					
Brush	Type					
Glass	Type					
Wheels	Type					
Handle	Type		Color			
Brackets	Type					

Rating	Dollar contributions to investment
0	No dollar contribution to initial investment
1	Very low dollar contribution to initial investment
2	Low dollar contribution to initial investment
3	Significant dollar contribution to initial investment
4	High dollar contribution to initial investment
5	Very high dollar contribution to initial investment

Estimate the yearly running and operational costs for customization that are associated with the same list of components/features in dollar values or on a (0 - 5) rating. (Refer to rating table below)

Customizable Components	Feature-1 + (Extra Yearly Overheads)		Feature-2 + (Extra Yearly Overheads)		Feature-3 + (Extra Yearly Overheads)	
Frame	Type		Color		Cutting Length	
Jamb	Type		Color		Cutting Length	
Interlock	Type		Color		Cutting Length	
Heel	Type		Color		Cutting Length	
Fly-screen	Type		Color		Cutting Length	
Rubber	Type					
Brush	Type					
Glass	Type					
Wheels	Type					
Handle	Type		Color			
Brackets	Type					

Rating	Dollar contribution to yearly operational expenses
0	No dollar contribution to yearly operational expenses
1	Very low dollar contribution to yearly operational expenses
2	Low dollar contribution to yearly operational expenses
3	Significant dollar contribution to yearly operational expenses
4	High dollar contribution to yearly operational expenses
5	Very high dollar contribution to yearly operational expenses

Estimate the additional storage area requirements for customization that are associated with the same list of components/features in 10ft^2 or on a (0 - 5) rating. (Refer to rating table below)

Customizable Components	Feature-1 + (Extra Storage Area)		Feature-2 + (Extra Storage Area)		Feature-3 + (Extra Storage Area)	
Frame	Type		Color		Cutting Length	
Jamb	Type		Color		Cutting Length	
Interlock	Type		Color		Cutting Length	
Heel	Type		Color		Cutting Length	
Fly-screen	Type		Color		Cutting Length	
Rubber	Type					
Brush	Type					
Glass	Type					
Wheels	Type					
Handle	Type		Color			
Brackets	Type					

MOC	Contributions to storage space
0	No contribution to storage
1	Very Low contribution to storage
2	Low contribution to storage
3	Significant contribution to storage
4	High contribution to storage
5	Very high contribution to storage

5) Setting a target for each goal:

Set specific targets for each of the objectives and resource consideration that were determined.

TARGET

		Satisfaction Units (%)
A	**Increased customer satisfaction over the standard**	*50 %*

TARGET

		Additional Percentage Market Captured (%)
B	**Additional market growth targeted over the standard**	*40 %*

TARGET

		Size of Investment (%)	Investment in ($1000)
C	**Initial investment costs consideration for customization**	*20 %*	

TARGET

		Size of Investment (%)	Extra Overheads in ($1000)
D	**Yearly operational expense consideration for customization**	*25 %*	

TARGET

		Storage Space (%)	Storage Space in (ft^2)
E	**Additional storage area consideration for customization**	*60 %*	

6) Actual or Recommended Customization Status:

Suggest customization solutions for each of the identified components/features (Check example below):

Customizable Components	Feature-1	Degree of customization	Feature-2	Degree of customization	Feature-3	Degree of customization
Frame	Type	2	Color	Any	Cutting Length	Continuous
Jamb	Type	2	Color	Any	Cutting Length	Continuous
Interlock	Type	2	Color	Any	Cutting Length	Continuous
Heel	Type	2	Color	Any	Cutting Length	Continuous
Fly-screen	Type	2	Color	Any	Cutting Length	Continuous
Rubber	Type	1				
Brush	Type	1				
Glass	Type	Any				
Wheels	Type	3				
Handle	Type	20	Color	Any		
Brackets	Type	3				

Example:

10	Handle	Models	20	Coating Color	50	

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