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A Study of How Model-centric Engineering Relates to Time-to-Market and Agility to Accommodate Customer-Required Changes

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A STUDY OF HOW MODEL-CENTRIC ENGINEERING RELATES TO TIME-TO-MARKET AND AGILITY TO ACCOMMODATE CUSTOMER-REQUIRED CHANGES

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ABSTRACT

As customers increasingly demand immediate product variation, companies are required to shorten product design and manufacturing life cycles to remain competitive. The ability to respond quickly to continuous and unexpected change is the key to success in the manufacturing industry (Yu, Liu, & Chen, 2005). As a result, manufacturing firms are using model-centric engineering (MCE) in product development to remain competitive in their ever-changing global environment.

The purpose of this study was to investigate the relationship between the use of model-centric engineering and a firm's competitiveness as defined by time-to-market and agility to accommodate customer-required changes. The study focused on two areas. The first area of focus defined the current model-centric environment in the manufacturing industry by factors such as level of MCE usage, years of MCE experience, discrete employee MCE job functions, and extent of MCE implementation. The second area of focus concentrated on MCE utilization as it relates to a company's competitiveness. This relationship was achieved by comparing a firm's level of MCE usage to its time-to-market, agility to accommodate customer-required changes, and company sales. Contingency tables, Fisher's exact test of significance and logistic regression were used to test hypotheses comparing the relationships of key variables.

From the results of this study it was concluded that there are some relationships between variables of MCE and a firm's competitiveness defined by the initial time-to-market and the firm's agility to accommodate customer-required changes. These relationships concerning MCE

were not based upon the software itself that supports this method but more from the MCE's relationship with the firm's business systems. Over 75% of the issues logged by the survey relate to a firm's way of managing MCE and not the functionality of the software. Through hypothesis testing, items such as co-location of engineers, training of employees, and consistency of implementation and usage of the MCE tools were found both to have impact on time-to-market and the agility to accommodate customer-required change. Per the survey results, 45% of the engineers located in the same building tend to have quicker time-to-market than did engineers segregated in a different location. Proper training and implementation is also important to create and sustain an educated workforce in an MCE environment. Even though 83% of the respondents indicated their staff received training, several of the issues of MCE led back to training-related items.

A MCE methodology is more than having capable computer-aided tools for the design and process development. MCE requires a strong foundation of policies, procedures, and protocol to allow the computer-aided software to function as it is intended and not hampered by a restrictive or unorganized business system.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Global competition and unpredictable industry factors are forcing today's manufacturing firms to evolve for their survival. The extent of this evolution varies by industry, but the necessity for change is critical and overarching nonetheless. As markets become increasingly global and diversified, manufacturers with the ability to adapt quickly and continuously to unexpected change cite agility as a key factor for their success (Gunasekaran, 1998).

Economic and technological globalization has allowed companies worldwide to have the same access to advanced technology, thus enhancing their prospects for competing in the world market (Freidman, 2005). Cheaper labor and advancements in distant communication, information sharing, computers, and the Internet have given companies of all nations the ability to be competitive in markets that were once dominated by the United States and other advanced countries. The speed and agility with which new worldwide competitors use these advancements will dictate the level of their success in the global market (Friedman, 2000).

But large corporations are not the only firms driving industry competition. Entrepreneurs and small businesses are embracing—and even pioneering—these advancements, further fueling the competition. Thomas Friedman (2000) states, "Today's globalization is unique because what only corporations once accomplished is now being done by individuals with small business and entrepreneurships, allowing them to reach around the world farther, faster, cheaper, and deeper."

Table 1 illustrates the global competitive index rankings from 2008 to 2009 compared to the current 2009 to 2010 time frame (World Economic Forum, 2009). These rankings were calculated from publically available data and a comprehensive executive opinion survey conducted by the World Economic Forum. The survey was administered to more than 13,000 businesses in 133 different world economies to capture a broad range of factors affecting an economy's business climate (World Economic Forum, 2009).

Table 1

"Current" Global Competitiveness Index Ranking and 2008-2009 Comparisons

Country/Economy	GCI 2009 - 2010 Rank	GCI 2008 - 2009 Rank
Switzerland	1	2
United States	2	1
Singapore	3	5
Sweden	4	4
Denmark	5	3
Finland	6	6
Germany	7	7
Japan	8	9
Canada	9	10
Netherlands	10	8

Before the widespread growth and evolution of technology, companies mainly concentrated on quality and manufacturing efficiency to remain competitive in their smaller business niches (Li, 2004). But as technology becomes more advanced and globally shared, competition is an increasingly prominent concern for the manufacturing sector (Ohashi & Shin, 2009). Utilizing tools such Total Quality Management and Lean Six Sigma, even manufacturers in developing countries can now provide high quality and reasonably priced products to customers, giving these countries access to once specialized areas that are now highly competitive markets. This globalization of manufacturing and technology allows the consumers more options regarding suppliers to better satisfy their product needs. Even though quality and efficiency are still important factors in a business's success, now firms must quickly and effectively react in an ever-changing global market to remain competitive.

As technology levels the manufacturing playing field, trends such as shortened product life cycles, customization requests, and rapid technology advancement are adding competitive demands to today's manufacturing market (Saad & Gindy, 2007). Companies are not only required to address these key elements for the sake of their customers, but also due to heightened global competition, they have to resolve these issues more effectively than their competitors. National and global competition has intensified creating shortened product life cycles, requiring firms to consistently and proactively satisfy the needs of their customers (Hai, Anderson, & Harrison, 2003). This increased worldwide competitiveness has escalated the importance of customer satisfaction, requiring timely and customized services to ensure competitive agility (Gunasekaran, 1998).

Results from a recent study from the Aberdeen Group (illustrated in Table 2) pinpointed the top five business pressures firms are facing and the strategic initiatives they used to counteract these pressures in the current manufacturing market (Aberdeen Group, 2006). The key pressures all focused on consumer needs—not just regarding cost or quality, but also regarding reduced time-to-market and overall customer satisfaction. Faced with an ever-growing selection of manufacturing firms from which to choose, customers are demanding faster time-to-market and rapid response to their customized needs. Manufacturing firms who want to succeed and stand out from the competition are obligated to comply.

Table 2

Top Five Business Pressures and Strategic Actions

Business Pressures	Percent	Strategic Actions	Percent
Shortened Time-to-Market	65%	Improve Prod. Performance/Quality	49%
Customer Demand for New Products	47%	Improve Development Efficiency	42%
Complex Customer Requirements	43%	Lower Internal Manufacturing Costs	25%
Accelerated Prod. Commoditization	29%	Develop New Markets w/ Innovation	17%
Competitive Products	27%	Decrease Customer Response Time	17%

Customer demands for products tend to change rapidly and frequently. In response to these demands, manufacturers must adapt their products to meet the needs of the customers in a shorter time frame in order to remain competitive (Ohashi & Shin, 2009). "The success of a company's future will depend on how effective [it is] in achieving rapid, flexible, and integrated product design and development in a reduced market time. To thrive in the emerging market conditions, it has to be capable of rapidly responding to market trends and operating as an efficient member of an extended and increasingly global supply network" (Saad & Gindy, 2007).

Ensuring customer satisfaction requires the ability to be agile and rapidly implement changes to meet customer demand. In an emerging business era that embraces change as a cornerstone, product success and survival are increasingly difficult to ensure (Onuh, 2006). Therefore the key to success, in addition to the ensuring customer expectations of high quality and efficiency, is the ability to proactively and successfully adapt to market and customer needs. Manufacturers must rapidly develop and produce newly customized products to effectively respond and compete.

To address these issues, manufacturing firms are now implementing new innovative methodologies, such as model-centric engineering (MCE). MCE-focused technological tools attempt to narrow time-to-market by reducing the time required to design and manufacture products. They also aim to improve customer satisfaction by providing flexibility to quickly react to customer needs. Likewise, with the ability of MCE tools to seamlessly integrate with other strategies already in place (such as Lean Manufacturing), companies can continue to employ proven solutions for the traditional competitive factors of quality and efficiency.

As technology continues to innovate and grow, so too do the tools for product design and manufacturing. For example, the use of three-dimensional computer models over two-dimensional blueprints has provided the foundation for the new MCE design method (Herron, 2008). By establishing a three-dimensional model as its core source, MCE centralizes all design, process, and inspection information. The intent of the model-centric environment is to provide a single source of information, enabling quick reaction to change and fewer design errors. This is accomplished through the maintenance and manipulation of one centralized design, reducing data duplication throughout a product’s life cycle.

Model-Centric Engineering

Traditional product development follows a linear flow. The next phase cannot start until the previous phase is completed (Rehg & Kraebber, 2005). For example, process planning cannot start until the process engineer receives the technical data package. Likewise, the technical data package cannot be released until the drafter is finished with detailing the design. Furthermore, the detailing cannot occur until the design engineer ensures that the design meets the customers' form, fit, and function requirements. Each step of the process requires the completion of the previous step. If there is a design change during any of these steps, the entire process stalls until the information can filter through all the requisite product development levels.

With traditional product development flow, information travels from work group to work group, with each group incorporating their specialized fulfillment of the customer requirements into the product manufacturing cycle. Such transfer of data provides an opportunity for miscommunication and logistical issues when engineering changes or customer-required changes occur. It also sections the product development process into autonomous silos, limiting the overall performance of the product development cycle as a whole. See Figure 1 for an example of the traditional transfer of data during a product's manufacturing life cycle (Herron, 2006).

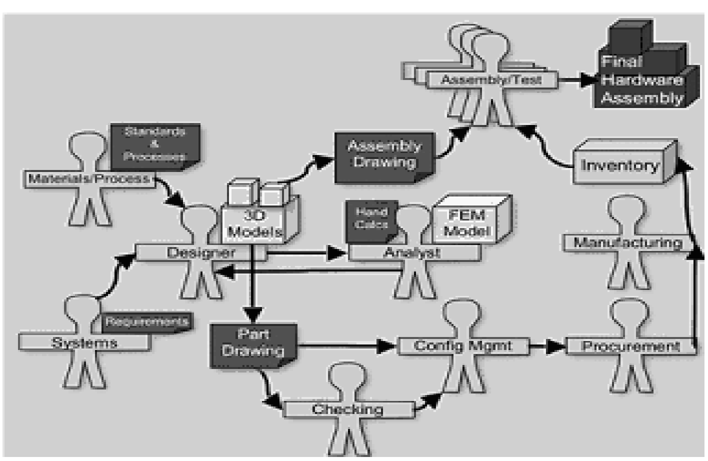

Figure 1. Communication Path for the Traditional Design Method

To minimize some of the communication hurdles of the traditional product design cycle, some firms have incorporated concurrent engineering, which provides a more structured, team-based product development method. Concurrent engineering is intended to increase communication and collaboration through teamwork and development; however, product and process information may be isolated in work cells, not visible to the entire team.

With MCE, a three-dimensional, computer-generated model functions as the central hub of the design and manufacturing phase (Herron, 2008). This model serves as the single source to hold all critical product information, from design through process. With the product information all in one location, the design and process development become intertwined, enabling an enhanced concurrent engineering environment. Figure 2 illustrates the concept of this model-based design approach (Herron, 2008).

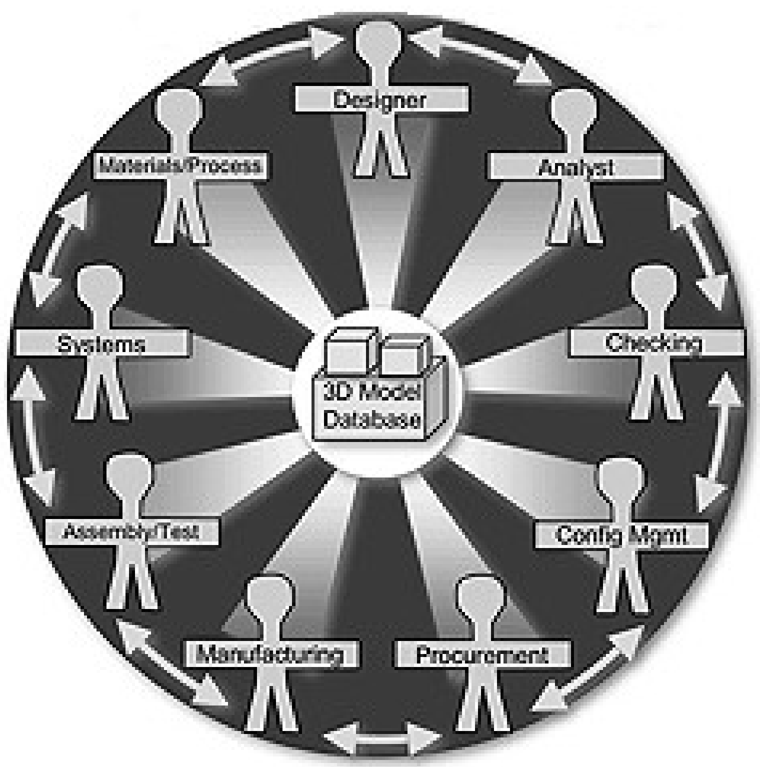

Figure 2. Communication Path for the Model-Centric Method

The benefit of using MCE is a shortened product life cycle. By synchronizing design and process information concurrently in a centralized data warehouse, companies can effectively communicate and meet the design and process requirements needed to begin production (NGMTI, 2005). The model-centric design also streamlines the evaluation of design alternatives early in the engineering process, optimizing performance and reducing or eliminating expensive late-stage design changes. This is accomplished by allowing the concurrent design of both the product and process by identifying and satisfying the needs and issues of both parties as the product is developed. Therefore, with the MCE approach, manufacturing companies can reduce time-to-market and increase their ability to accommodate changes required by their customers. A single digital representation of the product and process—for all design and manufacturing phases—limits the need for reproduction drawings and prototypes (Fireman, 2007). The single model contains all of the information of the product configuration. Thus, it is easily maintained, reducing potential product configuration issues of the traditional blueprint method.

As the need for competitive advantage and marketplace flexibility grows, companies are pursuing new technological tools and solutions to achieve greater market agility. Current research is ranking customer satisfaction as a key competitive factor and now as equal to quality and efficiency (Aberdeen, 2006). That is why more companies are implementing innovative MCE technologies: not only to better meet customer demand for high quality and efficiency, but also to ensure quicker reaction time and more specialized products.

Software advancements have enabled this move toward MCE. Now engineers can digitally produce and store designs in a central data repository, where other engineers can then use various software for analysis without tedious reproduction and manual copying (Harris, 2008). One example, Finite Element Analysis (FEA), looks at the strength of designs, products, and process simulations. It allows engineers to simulate product and process virtually, eliminating the need for prototyping (Aberdeen, 2006). Another example, computer-aided manufacturing (CAM), allows manufacturing engineers to import design data and quickly produce computer numerical control (CNC) machine programs for production. Computer-aided inspection (CAI) and Stereolithography are all processes that use a three-dimensional part directly from computer-aided design (CAD) solid modeling software to enable inspection capabilities and rapid prototyping. Regardless of what specific tools and methods a manufacturer employs, the trend is to store all product information in one centralized model to better ensure the success of the design, assembly, and inspection processes (Walker & Cox, 1999).

Need for the Study

Despite the growing amount of literature currently available on the subject of MCE, few studies have explored the relationship between MCE and company competiveness. A small amount of information exists concerning the implementation and management of the model-centric environment as a methodology; however, most of this research focuses on the technology that enables a model-centric environment, such as computer software and adaptable manufacturing hardware. This information is circulated by the software developers, who have an attributed bias to MCE. They advertise the benefits of decreased time and fewer design errors using a model-centric environment to promote their software product. Only a few empirical studies currently relate some portion of a model-centric environment to a firm's performance.

A thorough review of the current MCE literature did uncover some problematic issues related to the method. These included a lack of modeling standards and model complexity that would appear to hamper a firm's success. However, no study captured the full relationship, if any, between the potential issues with MCE and a firm's competitiveness.

The results of this study have assisted in validating and rejecting key assumptions that the use of MCE relates to industry competiveness. Firms can use this study as a qualitative resource when planning their engineering strategy. The study has addressed certain relationships between the implementation of a model-centric environment because this could be a direct link to a manufacturing firm's success.

Statement of the Problem

The firm's use of MCE and its relationship to their competitiveness, defined by initial time-to-market and the firm's agility to accommodate customer-required changes is unknown.

Statement of the Purpose

The purpose of this study was to investigate the relationship between the use of model-centric engineering and a firm's competitiveness as defined by time-to-market and agility to accommodate customer-required changes. The study focused on two areas. The first area defined the current model-centric environment in manufacturing by factors such as level of usage, years of experience, discrete MCE job functions, implementation, and usage. The second area concentrated on the relationship between the utilization of MCE and the competitiveness of a company. This involved comparing a firm's level of MCE usage to the firm's time-to-market and agility to accommodate customer-required changes.

Manufacturing firms commonly assume that utilizing MCE decreases time-to-market by reducing design time and productivity issues. They also assume that utilizing MCE provides greater agility for change, thus facilitating increased customer satisfaction. There is minimal scholarly published data to substantiate these assumptions. Software companies that create and market model-centric technology provide the most supporting data, but this data has inherent bias and may fail to recognize potential issues that inhibit the desired outcome of MCE. Having the functionality of engineering software does not necessarily mean success—neither does the incorporation of that software into current business systems. Conversely, it may be possible that software companies are not understating the extent to which the software provides greater agility and increased satisfaction, because they have not fully explored this correlation.

This research has attempted to answer such questions by developing a factual understanding of the efficacy of software in an objective manner. Through this study, the researcher has provided a clearer picture of MCE and its relationship to competitiveness.

Research Questions

1. What is the average level of MCE utilization among manufacturing firms?
2. What types of MCE implementation and utilization issues do manufacturing firms encounter?
3. Is there a relationship between the sizes of manufacturing firms due to the implementation of MCE and the initial time-to-market and agility to accommodate customer-required change?
4. Is there a relationship between manufacturing firms with or without discrete job functions of employees utilizing MCE and the initial time-to-market and agility to accommodate customer-required change?
5. Is there a relationship between manufacturing firm's experience levels of MCE and the initial time-to-market and agility to accommodate customer-required change?
6. Is there a relationship between manufacturing firm's engineering groups that are or are not co-located and the initial time-to-market and agility to accommodate customer-required change?

7. What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on initial time-to-market?
8. What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on agility to accommodate customer-required change?
9. What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, engineering location, software implementation, and MCE experience level on company sales?

Hypothesis Statements

1. H_{01}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the size of a manufacturing firm.

   H_{A1}: $\Theta \neq 1$. There is a statistically significant relationship between the initial time-to-market and the size of a manufacturing firm.
2. H_{02}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

   H_{A2}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.
3. H_{03}: $\Theta = 1$. There is no statistically significant relationship between the initial time-to-market and discrete MCE job functions.

H_{A3}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and discrete MCE job functions.

4. H_{04}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

   H_{A4}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

5. H_{05}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

   H_{A5}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

6. H_{06}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

   H_{A6}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

7. H_{07}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

   H_{A7}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

8. H_{08}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

H_{A8}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

9. H_{09}: $\beta_j = 0$. There is no statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

   H_{A9}: $\beta_j \neq 0$. There is a statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

10. H_{010}: $\beta_j = 0$. There is no statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

    H_{A10}: $\beta_j \neq 0$. There is a statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

11. H_{011}: $\beta_j = 0$. There is no statistically significant relationship between company sales trends and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

H_{A11}: $\beta_j \neq 0$. There is a statistically significant relationship between company sales trends and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Assumptions of the Study

- Respondents will have the knowledge and expertise to understand and answer each survey question.
- Respondents will answer each question to the best of their knowledge.
- Respondents will have no bias to any software or hardware firms.
- The survey is voluntary.
- The survey is not restricted to a bias environment that could influence respondent input.
- The respondents are representatives of the North American Industry Classification System (NAICS) and thus located in United States, Canada, or Mexico.

Delimitations and Limitations of the Study

This study is limited to MCE. It focuses on product concept, design, prototyping, analysis, and inspection as well as process development. It does not focus on material resource planning, scheduling, logistics, or supply chain issues.

- Surveyed participation is limited to members of the Society of Manufacturing Engineers (SME) employed by firms within the NACIS code 336.
- Surveyed responses are limited to the United States, Canada, and Mexico.
- Institutional or corporate policies may limit the number of potential survey participants.

- Respondents may not have been employed in an engineering-type position.
- Multiple respondents from the same company can respond to the survey.
- Respondents are limited to survey participation through an Internet survey only.

Terminology of the Study

Agile Manufacturing

This highly adaptable and flexible manufacturing practice quickly responds to customer demands. It aims to increase quality and lower costs associated with product development (Montgomery & Levine, 1996).

Agility

For the purposes of this paper, *agility* refers to a company's ability to make changes quickly and respond to customer need. The two key ways to measure a company's agility are lead time for engineering changes and reaction time for new product requests (Wallace & Bennett, 1994).

Computer-Aided Design (CAD)

CAD is the computer-based method of representing and analyzing the various stages of the manufacturing process with either two-dimensional software or three-dimensional solid modeling software (Chang, Wysk, & Wang, 1998).

Computer-Aided Engineering (CAE)

CAE is the analysis and evaluation of engineering design through computer-based techniques. It aims to quantitatively estimate the performance of mechanical structures and mechanisms using the finite element method and dynamic analysis (Nishigaki, Nishiwaki, Amago, Kojima, Tsurumi, & Kikuchi, 2002).

Computer-Aided Manufacturing (CAM)

CAM is a computer-based method for planning, managing, and controlling product manufacturing (Rehg & Kraebber, 2005).

Computer Numerical Control (CNC)

CNC involves the use of a dedicated computer-coded program to perform numerically controlled functions on a machining center or similarly controlled machine (Amstead, Ostwald, & Begeman, 1987).

Computer-Aided Process Planning (CAPP)

CAPP provides the link between design and manufacturing in a computer-integrated manufacturing (CIM) environment. Manufacturers utilize CAPP to develop product plans based on projected variables, such as cost, lead times, equipment availability, production volumes, potential material substitution routings, and testing requirements (Bose, 1999).

Concurrent Engineering (CE)

This engineering method involves the simultaneous or parallel consideration of all facets of the product development process, including design, analysis, manufacturing, testing, quality control, and marketing. Its goal is to reduce time-to-market and manufacturing cost, while improving product quality (Zhou, Carmi, Lau, & Koulas, 1996).

Design for Manufacturing and Assembly (DFMA)

This approach encompasses any procedure that considers all production factors, starting from the beginning of the product design process (Rehg & Kraebber, 2005).

Finite Element Analysis (FEA)

FEA is a numerical control technique that analyzes the functional performance of a structure by dividing the object into small blocks, known as finite elements (Rehg & Kraebber, 2005).

Globalization

Globalization refers to the way markets, technology, information systems, and telecommunication networks are interweaving, thus shrinking the global market from a size large to a size small (Friedman, 2000).

Model-Based Enterprise (MBE)

MBE is a computer-aided, systems-engineering approach to integrated product management. It enables decision making across multiple disciplines throughout a product's life cycle (Harris, 2008).

Model-Centric Engineering (MCE)

This methodology utilizes a three-dimensional computer-generated model as the center of the design and manufacturing phases of a product's life cycle (Herron, 2008). The three-dimensional model serves as the single source to digitally store the characteristic information of the product, from design through process. CAE and CAM software are typically used for MCE analysis and process development. The goal is to simulate and expedite the product design cycle.

New Product Development (NPD)

This refers to the overall process of creating a new product—from strategy, organization, and concept generation to marketing plan evaluation and commercialization (Ellram, Tate, & Carter, 2006).

Product Design

Product design is the stage of the product life cycle that determines the specifications required to meet the functional needs of the customer (Ellram, Tate, & Carter, 2006).

Product Life Cycle

This includes all of the successive stages of a product, including product development, market introduction, growth, maturity, and decline (Komninos, 2002).

Product Modeling

This process establishes the analytical and graphical representation of a product. It is used to communicate and preserve product configuration and functionality requirements (Chang, Wysk, & Wang, 1998).

Rapid Prototyping (RP)

This technologically based technique automatically generates physical models of mechanical components from a computer-based solid model (Musto, Howard, & Rather, 2004).

Stereolithography

Engineers use this additive fabrication process to build parts in a pool of UV-Curable photopolymer resin using a computer-controlled laser. Layers are added until the part conforms to the model (Cleveland, 2009).

Technical Data Package

This refers to the full collection of design, production, delivery, and maintenance data for a product. The goal is to communicate customer product definition, performance criteria, and method of verification to the appropriate deliverable sources.

Time-to-Market

This is the time required to complete the full product development cycle. It is a key performance metric for time-based competiveness in the manufacturing industry (Wallace & Bennett, 1994).

CHAPTER 2

LITERATURE REVIEW

As product life cycles shorten, demand for product variety grows, and the global market diversifies, manufacturers site the ability to respond to change as a pivotal factor for success (Yu, Liu, & Chen, 2005). Companies are looking toward technological advancements in product development as the key to addressing this need for change. These advancements allow manufacturers greater agility in navigating an increasingly competitive and evolving manufacturing landscape.

In this chapter a literature review is presented on the MCE design methodology. With the knowledge gathered by this review, the study has provided a comprehensive definition and assessment of MCE. Key MCE characteristics were defined and utilized to compare the utilization of MCE with a firm's competitiveness. The researcher has also used key MCE characteristics to develop an industry survey to gather data for this study. Analysis of this survey data has addressed the questions and provides a conclusion for the research problem defined in Chapter 1.

The use of MCE is on the rise, due to industry competitiveness that is driving companies to increase agility and decrease time-to-market. With technology advancements in engineering software, companies are rethinking new product development processes in order to meet these competitive demands (Ispas, Zapciu, Mohora, & Anania, 2006).

Traditional product development is a linear process that inherently spent significant time moving product data from one stage to the next. There are also issues of miscommunication, data loss, the cost for prototyping, and potential rework—all further introducing more development time.

MCE, on the other hand, creates a single data repository for design and process information. This allows all individuals working on a product to access consistent information; therefore, reducing the communication concerns and data integrity issues typical of the traditional design methodology (Herron, 2006). With today's software advancements, this data can now be captured with three-dimensional modeling. The product data is located digitally in a computer-generated model, where additional software applications can further reduce design and process time (Musto, Howard, & Rather, 2004). Compared to the traditional design method, the efficiencies of MCE and its technologies may create more opportunities for firms to address time-to-market and customer satisfaction issues, thus better meeting competitive demands.

Solid Modeling

At the core of MCE is the model itself. This model serves as the data warehouse for all of a product's design and process information. A common method in creating this central point of information is solid modeling, defined as the use of computer-aided design software to generate realistic computer-based geometric models of mechanical components and systems (Musto, Howard, & Rather, 2004). Solid modeling was uncommon in manufacturing before 1996, due to high costs for the requisite equipment and software. Then in 1996, software competition skyrocketed with the introduction of the Windows 95 and Windows NT operating systems (Herron, 2006). This competition significantly decreased the cost of implementing solid modeling, which, in turn, caused solid modeling to quickly gain popularity in the education and manufacturing industries (Noaker, 1996). This sudden surge of low-cost, high-speed computing established an infrastructure to support computer-aided design, therefore increasing the use and capabilities of three-dimensional modeling software (Walker & Cox, 1999).

The benefit of the solid model is that a product can be manipulated and analyzed at each step in the design and manufacturing processes. The product is created within the software one step at a time, like building blocks, by adding items known as segments and features. These product segments and features are controlled by parameters, such as dimensions, providing a digital representation of the product design in progress. Figure 3 illustrates the assembly of a product, as modeled in Pro Engineer.

Solid modeling is becoming more prominent in many industries, including the automotive, defense, and aerospace markets. It is utilized for everything from simple assembly and small product design to large-scale assembly and production. Solid modeling also plays a major role in the discrete-part manufacturing industries, where precise part modeling and complicated assembly are required.

Three-dimensional solid modeling provides a way to illustrate all features of a mechanical part while manipulating multi-axis computer-controlled tools and inspection equipment (Walker & Cox, 1999). Engineers benefit from its:

- Easy-to-understand images of their designs.
- Ability to efficiently select and edit features of the part being designed.
- Immediate feedback, which helps engineers analyze and check each design step.

Figure 3. Solid Model Example of Parts Assembly Using Pro Engineer

Early applications of solid modeling focused on producing automatically correct engineering drawings and cutter path generation for numerically controlled machining (Requicha, 1996). Today, while solid modeling still compliments non-electronic data for traditional design archival processes, the three-dimensional model also provides a complete digital CAD-CAM representation of a product. This is then digitally stored on a computer or server, eliminating the need for paper archives (Walker & Cox, 1999).

Solid modeling has evolved not only to provide the fundamental tool set for a large class of products and processes, but also to perform the geometric calculations required by a wide variety of applications (Thilmany, 2007). For both large and small companies, solid modeling has become critical to product conceptualization, product design, engineering analysis, manufacturing planning, and documentation (Walker & Cox, 1999).

Due to a recent explosion of research and publications on the subject, today's engineers have ever-increasing access to a rapidly evolving body of knowledge on solid modeling (Requicha, 1992). The wide variety of new software created to facilitate this rise in solid modeling popularity includes Pro Engineer, Unigraphics, Catia, Solid Works, and Ideas. Academics are also spending more time adapting curriculum to support these technological advancements (Walker & Cox, 1999). As products become increasingly complex and traditional software increasingly limited in scope, the amount of new research and software options will continue to propel the growth of this rapidly evolving engineering method.

CAD, CAE, and CAM

Computer-aided design (CAD) is defined as using a computer in the design process for both representation and analysis. It can refer to the use of either two-dimensional or three-dimensional modeling software (Chang, Wysk, & Wang, 1998). CAD originated in the mid-1960s as an early graphics editor limited to lines, circles, and arcs. Then in the 1970s, three-dimensional solid modeling facilitated the containment of design information for the production of drawings and limited engineering analysis. In the 1980s, as a result of price drops for personal computers and software, CAD became more popular among industry and academia. The CAD packages of the time were mostly two-dimensional software solutions, such as AutoCAD and CAD KEY (Rehg & Kraebber, 2005). Today, CAD has further evolved into a three-dimensional world, where two-dimensional drawings are becoming outdated, and solid modeling is highly preferred for data sharing. CAD software such as Pro Engineer, Unigraphics, and Catia has a wide range of functionality to fully design and document a product design. As technology continues to evolve, modules increasingly interface with CAD to better facilitate computer-aided engineering.

Computer-aided engineering (CAE) is defined as the analysis and evaluation of engineering design using computer-based techniques to calculate operational, functional, and manufacturing parameters too complex for manual methods (Rehg & Kraebber, 2005). It is also more loosely associated with software technologies that utilize CAD data for engineering analysis. Finite element analysis software is the most common type of CAE software. It is typically used to analyze product designs based on structural strength and fatigue.

There are many product simulation tools associated with CAE. These tools allow engineers to simulate the function of products by analyzing interactions across structural, fluid, thermal, and electromagnetic domains. Additionally, they assess software logic, electronics, and mechanical effects (Toupin, 2008).

Rapid prototyping is a CAE-based method that utilizes solid modeling to decrease the prototype phase of a product. It is used for design verification and representation with the ultimate goal of reducing the time and cost associated with full-scale prototypes. It was introduced in 1984, and 3D Systems made rapid prototyping software commercially available in 1988 (Jacobs, 1992). Today's engineers now have a variety of options for fabricating prototypes directly from CAD models using rapid prototyping. This is due to an increased acceptance and demand for solid and surface modeling (Meier, Smith, & Devlin, 1995). CAE software, used in conjunction with CAD software, allows design engineers to virtually build and prototype a design, minimizing errors before the first physical product is constructed and thus potentially shortening time-to-market and increasing a firm's competitiveness (Thilmany, 1999).

Computer-aided manufacturing (CAM) is the effective use of computer technology in planning, managing, and controlling the manufacturing and production enterprise (Rehg & Kraebber, 2005). It encompasses a wide spectrum of manufacturing applications, all utilizing a computer to integrate plant operations (Chang, Wysk, & Wang, 1998). CAM software allows engineers to utilize CAD data to virtually create machine code for use in a computational numerical control (CNC) machine. It is commonly utilized for programming equipment, such as machining centers and robots. Using CAM lowers the likelihood of human error in programming by allowing engineers to validate programming before performing operations.

CAM is also used for process planning and simulation. In process planning, it facilitates the analysis of the process and part routings to determine product flow and work instructions. This analysis can then provide operators with information needed to more efficiently perform work tasks. In process simulation, it assists with the verification of the manufacturing process to determine product flow and operator ergonomics.

CAD, CAE, and CAM provide the three basic technological components of MCE. Each addresses one key stage of the product design cycle, from conceptual development as a solid model, to engineering analysis and testing, to final process design and planning. However, while advancements in software technology may increasingly integrate these components, moving to a strictly digital solution for the product design cycle may still present problematic issues.

Roles and Responsibilities of Model-Centric Teams

In the 1970s, most manufacturers did not have a formal new product development process to manage product life cycles. This resulted in late designs and budgeting problems (Coffin & Allen, 2008). Then in the 1980s, Bob Cooper of McMaster University researched and developed a new area of product development that organized the process into gates and stages

(Cooper, 1994). He called it the Stage-Gate Process. Laying the pathway for a more organized method of product development, it offered built-in checks and balances. Thus, management had more confidence in making effective decisions and knowing when to move to the next stage of product development. The result was a basic linear flow for product development.

In typical design methodology, manufacturers employ engineers, designers, and drafters, each with separate job functions and responsibilities. The engineer is responsible for the overall performance of the product; the designer creates the concepts and functionality of the product; and the drafter makes the design producible by creating detailed drawings and production prints. Each of these positions executes its own tasks, rarely overlapping with the other two.

However, with three-dimensional modeling, software companies are now re-evaluating the traditional design methodology by combining all three positions into one (Aberdeen Group, 2006). The drafter, in particular, has become less necessary as a separate position because manufacturers are replacing drawing boards with CAD technology. Figure 4 illustrates the new team dynamic for product development in today's manufacturing firms (Aberdeen Group, 2006). The chart compares the drafter-engineer mixes for *Best in Class*-rated firms and *Average*-rated firms. The Aberdeen Group assigned these rankings based on revenue, product cost, development cost, launch dates, and overall cost. The top 20% were categorized as *Best in Class*, while the following 50% were categorized as *Average*. The study demonstrated that companies are moving away from having separate drafters and detailers in favor of strictly engineer-based product development teams. Such teams include engineers who use CAD, CAE, and CAM tools to perform product design and process design, thus melding the traditional job function of engineers, designers, and drafters.

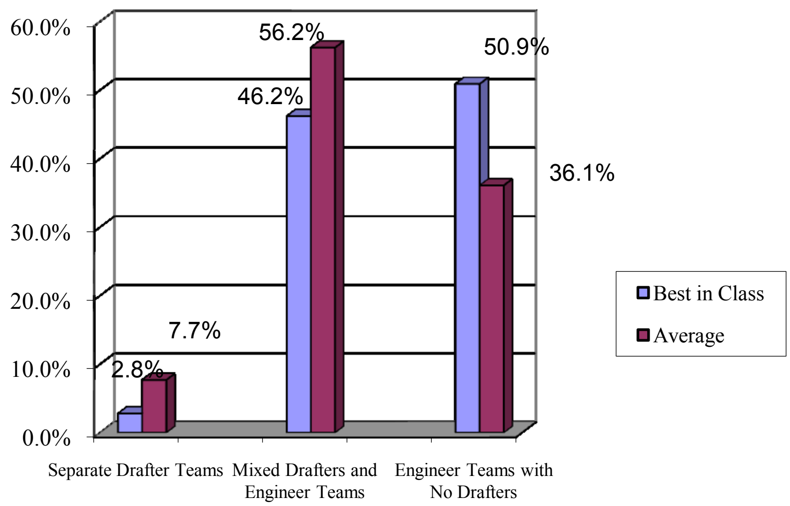

Figure 4. Team Dynamic for *Best in Class* and *Average* Firms

Due to the growing complexities of product development, companies are increasingly relying upon engineers to directly develop and design their products. If engineers are not involved during the modeling portion of design, serious unintentional mistakes can happen due to misinterpretation and ignorance (Woods, 2002). By having the engineer model the design, manufacturers can increase their odds of correct design intent, eliminate costly specialty positions, create greater design flexibility, and decrease overhead (Aberdeen Group, 2006).

Jean Thilmany, an associate editor with the American Society of American Engineers, wrote that the boundaries between traditional drafters and design engineers are becoming grayer as CAD tool implementation increases. Though design engineers will require much time and training to become proficient in solid modeling, with proper software and training, they are expected to soon eliminate the need for drafters in the model product design process (Woods, 2002). That said, there still is not a computer tool for every design or manufacturing problem. A skilled design engineer will know when to use the CAD, CAM, and CAE tools versus when to rely on long-hand analysis (Loew, 2009).

The main differentiation between CAD engineers and design engineers is this: CAD engineers use CAD tools to document models, whereas design engineers create the designs that are documented in the CAD model. Effective design engineers all have the following characteristics (Loew, 2009):

- Fundamental mechanical engineering knowledge of statistics, dynamics, component design, and electrical engineering
- A complex understanding of design methodology, product requirements, and the process of translating that information into CAD, CAM, and CAE
- The ability to perform stress and load analysis for data integration into analysis tools, such as FEA
- Fundamental knowledge of the assembly, fabrication, and machining processes
- A team-based mentality for estimating costs, reviewing designs, and providing quality reviews and feedback

Model-Centric Engineering

MCE derives from a much larger product development method known as model-based enterprise. The main difference between the two is the function involved during the product life cycle. Model-based enterprise is comprised of model-based engineering and model-based manufacturing, along with product strategy and resource management. Conversely, MCE is focused on just the design engineering and process planning. Both of these methods are based on having a central data repository, but the extent of information contained—and who uses that information—differs.

In model-based enterprise, a three-dimensional model contains the complete design requirements of the product, and all of that information is available from a single source. This source fully represents the complete design and is accessible electronically throughout all areas of the company during the entire life cycle of the product (Renaissance Group, 2008). Figure 5 illustrates the communication flow of model-based enterprise (NGMTI, 2005).

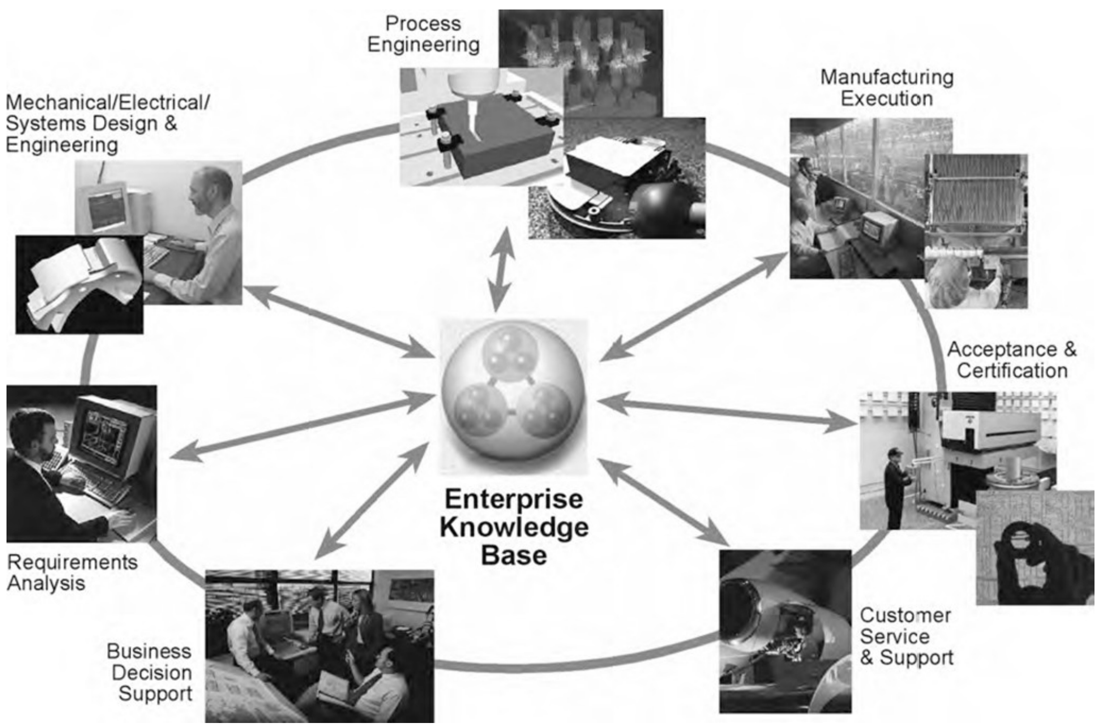

Figure 5. Model-Based Enterprise Communication Flow

With model-based enterprise, models are used to drive and enable the complete function of the enterprise, from engineering and manufacturing to product strategy and resource management. It facilitates a highly integrated environment, enabling multidisciplinary decision making that takes into account the entire product life cycle (Harris, 2008). While many leading manufacturers use modeling and simulation tools extensively in their engineering and business processes, the model-based enterprise is much more than the use of modeling and simulation software. It is methodology that changes all of a business's processes and the entire culture of the organization (NGMTI, 2005). As illustrated in Figure 6, model-based enterprise involves the full spectrum of product development, beyond product design to areas such as resource management and strategic management (NGMTI, 2005).

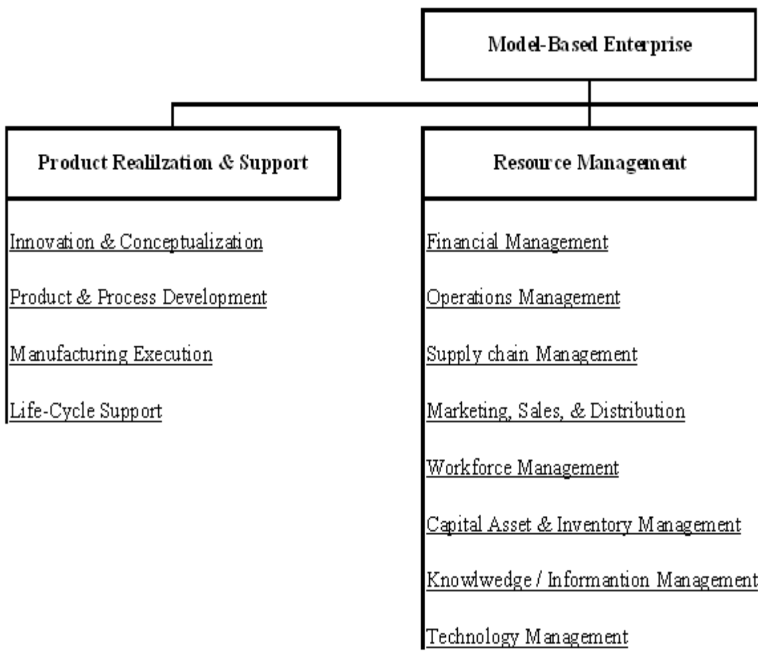

Figure 6. Model-Based Enterprise Top-Level Functions

Model-based enterprise consists of three crucial and separate functions: product realization and support, resource management, and strategic management. The Next Generation Manufacturing Technology Initiative (2005) further defines these functions as follows.

Product Realization and Support

This function includes all activities required for the conception, development, production, and support of an enterprise's products—all the way to the appropriate disposition of the product at the end of its useful life. At the core of a manufacturing firm's mission is product realization: the design, fabrication, and support of products to generate revenue and fulfill the needs of customers and other stakeholders (NGMTI, 2005). At the foundation of product realization are model-based engineering and model-based manufacturing. These two areas further break down into product and process design. As the name implies, all engineering design and development falls within product realization and support. Likewise, model-based manufacturing produces the process design, which relies upon the same model as model-based engineering.

Resource Management

This function involves all activities associated with the enterprise, including the oversight of all production operations, support operations, supply chains, sales channels, distribution mechanisms, human resources, finances, technology resources, and other assets.

Strategic Management

Enterprise management includes all of the activities required for company leadership to guide the enterprise, based on current, complete, and accurate information. Strategic management is separate from resource management in that strategic management is not specifically concerned with the enterprise at an operational level (although the two functions are interrelated).

In a model-based enterprise, all three business functions are engineered to pull needed information from product and process models linked to knowledge sources, so that information can be effectively applied to the appropriate business models. When all business processes are designed into an integrated model across the enterprise, all functions can then share and act upon collaborative requirements, knowledge, and resource information. Integrated process modeling also provides greater flexibility to accommodate change.

A model-based enterprise dictates a mindset of virtual experience in concert with physical experience. In a model-based culture, simulation and modeling systems replace most physical prototyping with digital prototyping, which gives firms the ability to manufacture a product correctly on the first try, every time. Life cycle costs—inherited by the customer as well as company operational budgets—directly correlate with decisions made early during product and process development. A lack of processes and tools to support a model-based approach may significantly impact these costs. The implementation of model-based enterprise requires an up-front process designed to make life cycle-impacting decisions while designs are still fluid (Walker & Cox, 1999). The basic notion of the model-based enterprise is not simply the application of concurrent product development, but rather a focus on the tools and the interoperability of such tools, thus optimizing design, manufacturing, and supportability (NGMTI, 2005).

At the center of MCE is three-dimensional computer-generated modeling, considered critical to the design and manufacturing phases of a product life cycle (Herron, 2008). The three-dimensional model serves as the single source for all information regarding the development of a product, from design through processing. With the product information located in a single source, the design and process development happen jointly, enabling an enhanced concurrent engineering environment. This collaboration and communication is illustrated in Figure 7 (Herron, 2006). MCE is similar to model-based enterprise in that it couples the model-based engineering and model-based manufacturing components of the model-based enterprise approach into one function. However, it disregards the resource and strategic management functions central to the model-based enterprise.

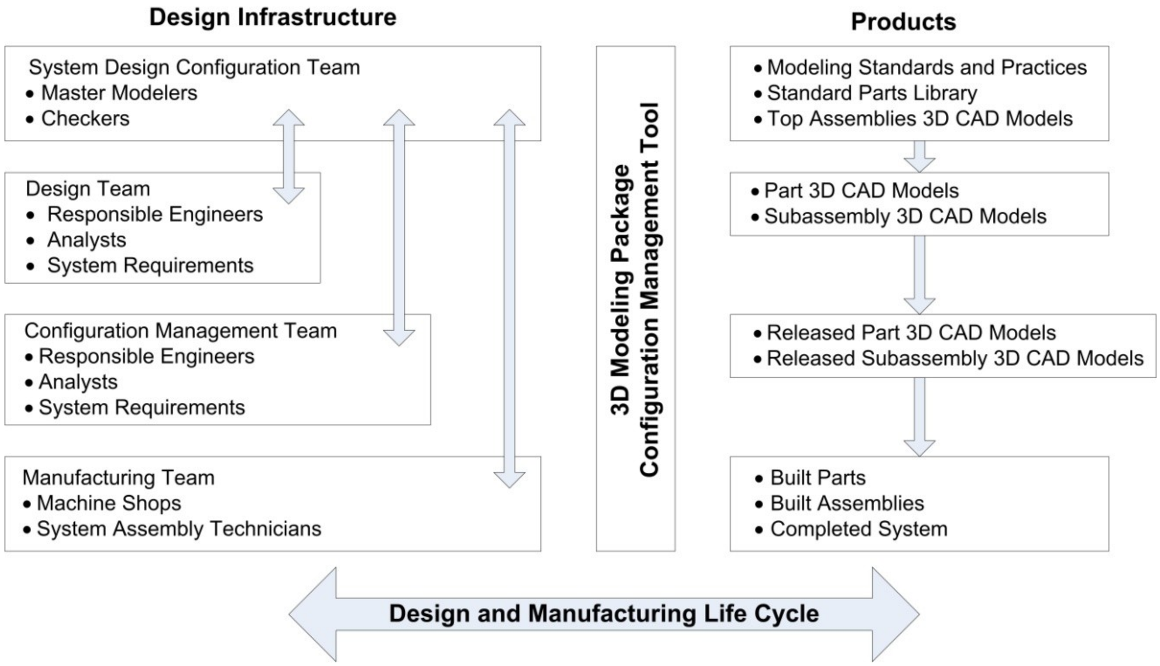

Figure 7. Communication Paths during the MCE Cycle

As software technology grows, so too does the feasibility and utilization of a model-centric environment. New software technology allows engineers to digitally produce their designs and store them in a central data repository, where other engineers can then use that technology to analyze their designs without any reproduction or manual copying (Harris, 2008). Examples include software tools such as Finite Element Analysis, which analyze the strength of the designs, enable product and process simulations without expensive prototyping, and facilitate instruction planning and more efficient training (Aberdeen Group, 2006). CAM software allows manufacturing engineers to import design data and quickly produce machine programs for production on CNC equipment. Other software applications, such as computer-aided inspection and Stereolithography, also use three-dimensional parts information directly from a solid modeling file to effectively inspect and efficiently prototype.

The key benefit of MCE is a potential reduction in the product design and build life cycle. This is achieved through the simultaneous facilitation of design and process, supported by a central data warehouse that contains all the requirements needed for full-rate production (NGMTI, 2005). A single digital product and process model replaces the need for drawing reproductions and prototyping (Fireman, 2007). As a result, the MCE approach streamlines design simulation and evaluation early in the engineering process, optimizing performance and reducing or eliminating expensive late-stage design changes. Thus, MCE can potentially reduce time-to-market and increase a company's ability to accommodate customer-required changes.

Since the single centralized model contains all of the product information, it is easily maintained, reducing the likelihood of configuration management issues, as is common with traditional drawing methods. This centralized method for storing product information is pivotal to the design, assembly, and inspection of parts because it facilitates greater configuration control, a more synchronized engineering environment, and potentially a more efficient design process (Walker & Cox, 1999). This is why many manufacturing industries continue to push for further research and development of MCE. For example, the aerospace and defense industries have partially implemented the method (with their Joint Strike Fighter and the Orion programs), but without the ability to create full formal designs to build release processes, they lack the comprehensive benefits of a true model-centric approach (Herron, 2006). Portions of the model-centric environment have been implemented by companies in a variety of industries, but beyond software research, companies must consider critical organizational and management changes to truly benefit from MCE's full potential.

Issues Pertaining to the Model-Centric Environments

Full implementation of MCE and solid modeling is hampered because of issues such as industry standards, certification processes, experience required, and software development limitations. Research teams and industry collaboration are currently working to resolve these issues, but until they are resolved, the true cost and productivity savings of MCE cannot be adequately calculated and realized (Herron, 2006).

At the core of MCE's success or failure is the software it relies upon. In the late 1980s, the most significant problem that MCE-focused engineers faced was the lack of interfacing between CAD and CAE (Thilmany, 1999). Software companies were designing software for independent tasks rather than full-function model-centric design. CAD software from one company would not directly transfer data from one type of CAE software to another. The first attempt to resolve this issue was the development of translation software. This software enabled the data to be universally recognized across technologies. However, in the process, it also created opportunities for data to be lost, negatively affecting manufacturing timelines and budgets.

Eventually this was resolved, but issues still remain with today's MCE software. For instance, CAD and CAM tools often communicate in an open format, requiring manufacturing engineers to interpret and manually transfer information into CAM tools and machines, creating opportunities for error (Thilmany, 2007). However, that is not to say that MCE software capabilities lack innovation and advancement. CAD and CAE suites are now on the forefront of concurrent design practices, giving engineers the capability to design and virtually build a product, while CAE software analyzes and flags potential design flaws prior to production (Thilmany, 1999). As more issues are resolved and more advancements are made, the benefits of MCE are expected to multiply.

Lack of standards is also a major issue with MCE. In the traditional design method, engineers would give a design to a drafter, who would then create a formal design standard with geometric dimensioning and tolerancing (GD&T), as well as surface finishes. Now designs are given to CAD operators or the engineers to model the design in a CAD system. The individual operating the CAD software determines the amount and type of information along with the completeness of the model; however, there are no international CAD modeling standards for solid model development as there are for two-dimensional drafting (Herron, 2006). To complicate the matter further, more companies are modifying the traditional hierarchy of designer, analyst, and drafter into just design engineers, assuming that, if CAD software can do all three functions, so too can individuals (Herron, 2006). Companies are under the impression that CAD software tools have eliminated the need for detailed design and analysis, greatly underestimating the importance of this critical part of the design process. As a result, companies may not allocate the appropriate amount of time and money to design and analysis, wasting time and money in the long run (Herron, 2006). Even though software is increasingly complex, it currently cannot recognize and resolve all potential design issues.

To further complicate matters, engineers are now graduating from college with an MCE focus that precludes two-dimensional drafting experience. With the movement toward solid modeling, universities are putting less emphasis on the traditional engineering fundamentals of two-dimensional drawing and GD&T (Herron, 2006). This lack of knowledge base, compounded with software limitations, inhibits the full realization of the potential of MCE. As a result, corporations are not yet fully committed to pursuing this next generation of product development (Herron, 2006).

Figure 8 illustrates some of the issues and fears preventing companies from transitioning to a model-based environment (Aberdeen Group, 2006). The chart categorizes companies into three sections: two-dimensional users with no plans to migrate, two-dimensional users with plans to migrate, and three-dimensional users that have already migrated. The largest concern for the two-dimensional users with no plans to migrate is the cost and time justification needed for implementation. The main concern for two-dimensional users that do have plans to migrate is the training and support required to implement three-dimensional model-based design successfully. The primary concern for the three-dimensional user already using three-dimensional models is having a standard method to manage those models. This is especially true for managing large complex models, which amplify not only the need for better standards, but also the need for the physical hardware required to process model information.

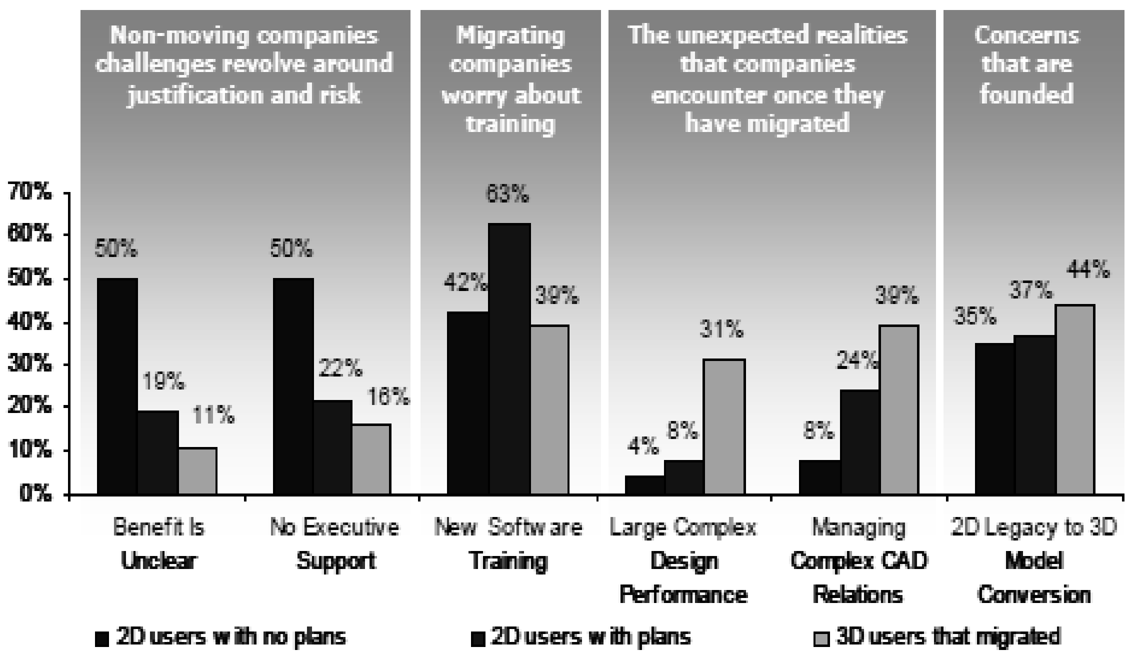

Figure 8. Fears of MCE

Figure 9 details application performance challenges of three-dimensional modeling. As the size of models increase, there are more performance issues related to regeneration and model retrieval times. These restrictions create the need for extra time, an increased likelihood of frustration and mistakes, resulting in decreased engineer productivity.

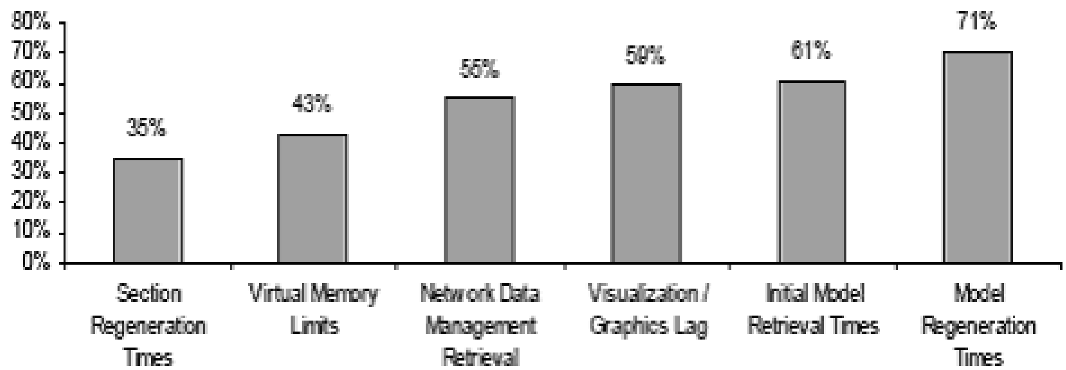

Figure 9. Application Performance Issues

There are many issues that could prevent the proper implementation of the model-centric method. Below are some of the most common:

- Lack of overall industry and corporate commitment.
- Lack of communication between all disciplines.
- Two-dimensional requirements for contract deliverables.
- Insufficient CAD implementation by suppliers.
- Inaccurate perceptions of the detailed drawing process.
- Lack of CAD standards and processes.
- Inadequate experience and certification.
- Hardware and software limitations.

Past Related Research on Model-Centric Engineering

Industry Collaboration on Model-Based Enterprise

In 2004, several manufacturing companies formed a consortium to produce an industry review of the MCE implementation. The consortium included companies such as Boeing, Lockheed Marten, Raytheon Missile Systems, Rockwell Collins, and Sandia National Laboratory. Their goal was to better meet (1) customer demands for higher performance at lower cost, (2) shareholder demands for greater returns, and (3) company demands for growth at minimal cost.

The consortium studied MCE's ability to:

- Optimize designs for all life cycle requirements of a product.
- Produce required information automatically to execute enterprise processes.
- Manufacture products in a virtual environment, where problems could be anticipated and resolved prior to production.
- Design for the best total value.
- Predict overall performance, thus reducing schedule slips and cost overruns.

Figure 10 illustrates their conclusions on the current state of MCE product development, as well as the changes they would like to foster. It overlaps model-based engineering and model-based manufacturing, which they describe as DFx (Harris, 2008). By considering a concurrent engineering method intertwined with model-based engineering and model-based manufacturing, the consortium's main goal was to find new ways to reduce design and process issues up front, when the design was still fluid.

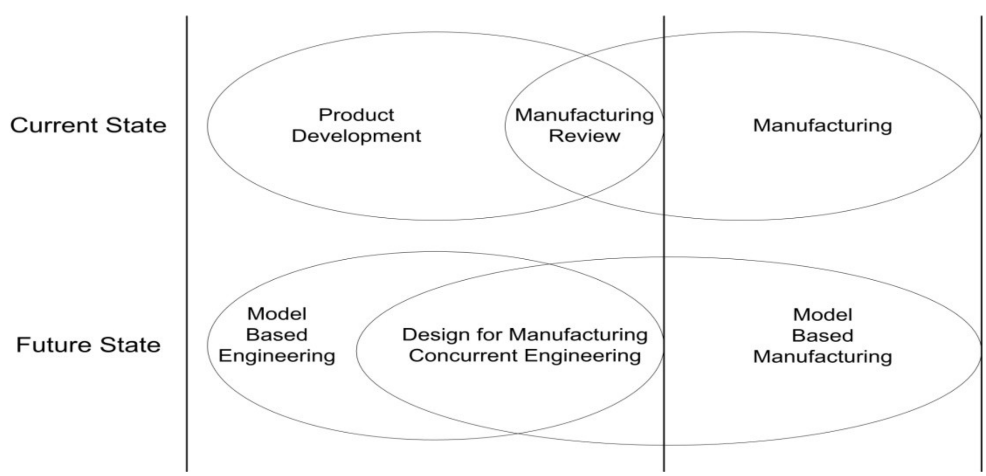

Figure 10. Consortium Analysis of Current and Future Product Development Interaction

More recently, the consortium has begun performing gap analysis between the current and future states of the product life cycle model. Along with this gap analysis, the consortium is pursuing other developmental projects within the model-based engineering and manufacturing realms, such as design deflection simulation, value stream mapping, and system engineering innovation. The goal is to disseminate new MCE knowledge to companies and universities involved in creating electro-mechanical systems and products for the aerospace and commercial sectors.

Next-Generation Manufacturing Technology Initiative (NGMTI)

NGMTI is a partnership between government and industry to accelerate the development of breakthrough manufacturing technologies that could strengthen the defense industrial base and improve the global economic competitiveness of U.S. manufacturers. It is sponsored by the Department of Defense, and its goal is to discover, analyze, and implement emerging technologies to better support the Department of Defense’s manufacturing needs. The partnership includes 175 manufacturing community leaders representing more than 75 different organizations. NGMTI is managed by the Advanced Technology Institute in partnership with the Integrated Manufacturing Technology Initiative and the National Council for Advanced Manufacturing. The program addresses the common requirements of the Department of Defense and industry in the United States with the following three-part strategy (NGMTI, 2005):

1. *Strategic Investment Plan.* NGMTI is working with hundreds of representatives of the manufacturing community to define compelling needs, map current research and development investments against those needs, identify critical voids, and develop a comprehensive national plan for focused manufacturing technology investment.

2. *National Investment Plan.* Building on the strategic investment plan, NGMTI has created the Industry-Government Forum—a coalition of industry, government, and research leaders working together to execute a strategic investment plan. The Industry-Government Forum convenes semiannually to review requirements and strategies.
3. *Technology Transition.* NGMTI is implementing strategies and processes to accelerate the maturation and implementation of new technologies in alignment with its strategic investment plan. These strategies include proof-of-concept experiments and a National Manufacturing Technology Test Bed Network for technological facilitation and widespread deployment. By integrating the resources of leading government and industry manufacturing laboratories, this network will provide nationwide advancements in manufacturing technology.

The NGMTI program is built around a series of six Thrust Areas. These areas provide a focused structure for managing technology requirements that cut across the nation's defense and commercial manufacturing base. The six Thrust Areas are:

1. Model-based enterprise.
2. Emerging process technologies.
3. Intelligent systems.
4. Enterprise integration.
5. Knowledge applications.
6. Safe, secure, reliable, and sustainable manufacturing operations.

These topics were selected based on input from industry and government focus groups to define the highest priority technology needs of the nation's manufacturing community.

The NGMTI program has already developed goals and objectives to meet the needs of the first Thrust Area: model-based enterprise. These goals and requirements are organized into 13 projects currently in progress. The total investment of these projects is expected to total $132 million during the time period of 2006 through 2013. The following are the 13 project descriptions as described by the NGMTI (NGMTI, 2005).

1. *Flexible Representation of Complex Models (84 Months, $33 Million).* This project was formed to develop a comprehensive product model rich enough to support all development, production, support, and end-of-life disposition activities throughout a product's life cycle. The resulting model is intended to have the flexibility and power to quickly provide the exact "views" needed to support all desired functions. The model (and its associated manufacturing and support processes) will integrate all needed information, either within the model or by linking to data from internal or external sources.
2. *Shared Model Libraries (39 Months, $9.1 Million).* This project will establish a common, robust framework for managing repositories of collaborative models. When assembled, these models can accurately simulate materials, products, and enterprise functions across different industry sectors. The project will also establish an initial library of such models to validate the technical feasibility and business value of the shared model library concept.
3. *Systems-of-Systems Modeling (32 Months, $4.4 Million).* The goal of this project is to demonstrate the various capabilities, approaches, and tools related to multi-level, multisystem modeling. It takes into account product, process, and life cycle functions for a representative set of products in a selected manufacturing industry

sector. The project intends to demonstrate how systems-of-systems modeling techniques can reduce product development time and cost, eliminate current needs for manual integration across enterprise processes, and deliver product and process designs optimized for performance across the product life cycle.

4. *Enterprise-Wide Cost Modeling (30 Months, $8.4 Million).* The goal of this project is to establish and manage comprehensive, highly precise, total product cost models that reflect not only traditional materials and direct production costs, but also design and investment factors, among other indirect influences. These cost models will not be static; rather, they will link to "live" sources of data, down to the lowest level of the supply chain.
5. *Intelligent Models (36 Months, $5.6 Million).* This project explores technology's capacity to understand, seek out, acquire, and act on the information needed to execute functions. The goal is to establish links between the physical modeling realm and logical models with product, process, and enterprise intelligence.
6. *Model-Based Enterprise Configuration Management (60 Months, $23 Million).* The intent of this project is to develop an integrated system to associate and trace the right information for all products and processes throughout a product's life cycle. It involves developing requirements and integration strategies for managing complex interdependent configuration entities, from the lowest level of a manufacturer's supply chain, across the full life cycle of a manufacturer's entire product line.
7. *Product-Driven Product and Process Design (38 Months, $7 Million).* The goal of this project is to develop modeling and simulation capabilities that will enable

product models to automatically drive downstream manufacturing and support applications. It is intended to demonstrate collaborative interaction between product and process models, to evaluate the current state of product and process model capabilities, and to provide business-case data regarding the impact of decisions made at each step of product design and manufacturing.

8. *Model-Based Life Cycle Management (66 Months, $13.5 Million).* This project aims to create and apply scalable, high-fidelity product life cycle models to support every phase of the product lifespan, through all tiers of the supply chain.
9. *Model-Based Real-Time Factory Operations (36 Months, $4 Million).* This project will develop real-time model-based technology to control all factory operations, including production and maintenance operations as well as active interfacing with asset, inventory, and facility management systems. Its goal is to provide models that establish the necessary operation control functions that integrate with material, product, process, and control models to deliver a comprehensive prototype system.
10. *Model-Based Distribution (39 Months, $6.8 Million).* The goal of this project is to create facilitating technologies and to conduct proof-of-principle demonstrations of model-based distribution capabilities that can support highly complex requirements, such as those for military systems. It will provide a generic system framework to support design for distribution, distribution planning, management, execution, and re-planning in response to changes on demand.
11. *Multi-Enterprise Collaboration (34 Months, $2.7 Million).* This project will provide the initial set of methods and standards required for seamless interaction

of model-based processes among supply chain members. It will also demonstrate these capabilities with a team of industry partners in a select manufacturing sector.

12. *Model-Based Resource Management (40 Months, $4.7 Million).* This project will develop model-based manufacturing technologies that will lay the groundwork for a resource management system that is modular, scalable, and built to address open software standards. It will give manufacturers a baseline for modeling, simulating, and directing control over all of their enterprise resources, while providing the flexibility needed to deal with the broadening scope, complexity, and functional requirements of organizational processes.
13. *Information Delivery to Point of Use (24 Months, $9.75 Million).* This project focuses on model-based technologies that deliver information to the point of use through flexible, affordable systems. It will demonstrate effective ways to share information from planning processes with the four primaries "execution systems" of the enterprise: manufacturing, product support, factory maintenance, and training.

The total investment of these projects is expected to total $132 million during the time period of 2006 through 2013.

Transition from Two-Dimensional Drafting to Three-Dimensional Modeling (Aberdeen Group, 2006)

In August 2006, the Aberdeen group researched the design engineering methodology of 520 companies. The survey provided a method of collecting data to address the following objectives:

- Assess the degree in which mechanical engineering and design impact corporate strategies, operations, and financial results.
- Determine the structure and effectiveness of existing mechanical design technologies.
- Review the benefits, if any, of mechanical engineering and design efficiency initiatives.
- Create best practices for mechanical engineering and design.
- Build a framework to assess mechanical design capabilities.

From this survey, the Aberdeen Group published a benchmark report of the transition from drafting to modeling. This report studied unspecified manufacturers categorized by their financial, process, and quality performance. These indicators included *Product Revenue Targets*, *Product Cost Targets*, *Development Cost Targets*, *Launch Dates*, and *Quality Expectations*. The Aberdeen Group used these key performance indicators to classify manufacturers into three categories: *Best in Class*, *Average*, or *Laggards*. The *Best in Class* manufacturers represented the top 20% of companies in the study. The *Average* manufacturers made up the next 50%, while the *Laggards* consisted of the bottom 30%.

The Aberdeen Group's findings illustrated that *Best in Class* companies were 40% more likely to have engineers using CAD directly, rather than designing and detailing separately. These companies were also 12% more likely to have their products designed electronically, completely eliminating the need for hand-drafted designs. Additionally, the *Best in Class* companies were 24% more likely to utilize CAD software to its full extent and 55% more likely to use extended downstream analysis software during the product development. All 100% of manufacturers classified as *Best in Class* also had new hardware to support three-dimensional modeling, whereas only 53% of the *Laggard* firms had made the investment. Furthermore, the

Best in Class companies met at least 84% of the KPI target measurements of this study. They produced an average of 1.4 fewer prototypes than the *Average* companies and had an average of 6.1 fewer design changes than the *Laggard* companies. The *Best in Class* manufacturers not only produced the most complex products, but they also managed to do so 99 days earlier and $50,637 cheaper than their counterparts.

Competitive Challenges of Manufacturing

The manufacturing sector, increasingly competitive due to globalization, has forced companies to find other ways to boost competitiveness. Simply having a low-priced, high-quality product is no longer enough. The combination of technology and lower global labor rates allows customers more options when searching for product suppliers. Specialized business niches with previously "guaranteed" customers will continue to decline as technology and manufacturing capabilities spreads worldwide. Manufacturers now have to focus on retaining current customers or attaining new ones, in addition to manufacturing their products. Even though efficiency and quality are still important competitive factors, customer satisfaction is increasingly critical in setting companies apart from the competitors. Time-to-market and agility to accommodate customer-required changes are two key areas of customer satisfaction that companies are targeting to increase business within their industries

First, let's consider time-to-market. As technology advances, product life cycles are shortening. A product's technology or market need may be applicable for only two years before an upgrade is warranted or another product replaces it (Melsa, 1999). Therefore, quick product development is crucial in meeting the aggressive schedules that both customers and technological advancements place on manufacturing companies. As Toffler predicted, "In the

21st century, it will no longer be the haves and have nots; the difference between success and failure on a global scale will depend on whether an organization is fast or slow" (Toffler, 1990).

Time-to-market can be categorized into three sections: front-end planning, product development, and product deployment (Melsa, 1999). During the front-end planning stage, a company defines its product, researches the market, and determines the production schedule. Then, in the product development stage, it focuses on the design of both the product and process, including finalizing hardware and software designs, prototyping, and determining the manufacturing needs. Finally, in the product deployment stage, the company releases the product into full-rate production. At this stage, testing and processing are complete, and production can be measured on its efficiency and quality. Figure 11 illustrates the full time-to-market interval for the development of a new product (Melsa, 1999).

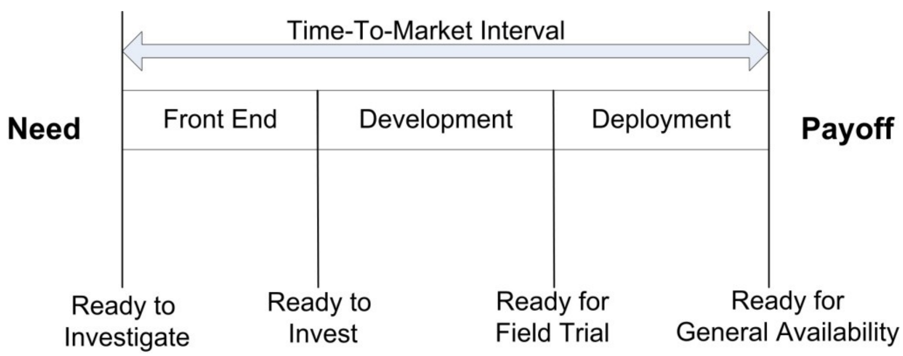

Figure 11. Time-to-Market Interval for the Development of a New Product

Decreasing time-to-market enhances a firm's competitive advantage. By utilizing up-front planning and "getting it right the first time," the company can reduce the number of design changes, thus increasing product quality. A shorter time-to-market also improves customer satisfaction because it allows for a quicker response to customer demand for new products or changes to existing products (Melsa, 1999). Firms that have a quicker time-to-market are often more profitable due to advance planning and up-front design, which reduces the potential for costly errors and issues after production begins.

For firms with a product life cycle shorter than three years, time-to-market is a key competitive advantage (Datar, Jordan, Kekre, Rajiv, & Srinivasan, 1997). Some of the ways manufacturers try to shorten their time-to-market include:

- Identifying customer needs earlier in the design process.
- Investing in new engineering capabilities, such as MCE.
- Utilizing concurrent engineering through cross-functional teams.

Along with pressures to design and develop increasingly complex products to meet customer demands, companies are now competitively forced to shorten their time-to-market (Aberdeen Group, 2006). The Aberdeen Group study "The Transition from 2D-Drafting to 3D Modeling," illustrated that companies must develop more products and get them to market faster due to:

- Shortened time-to-market (65%).
- Accelerated product commoditization (29%).
- Threatening competitive products (27%).
- Customer demand for new products (47%).
- Customer demand for increasingly complex products (43%).

Implementing a time-to-market strategy is similar to just-in-time manufacturing (Sandras, 1989). Traditionally, the use of specialists was common in the design process, wasting time waiting for individuals to do their sections of the work. But with just-in-time manufacturing, teams are cross-functional, capable of performing multiple tasks. This facilitates better communication between more members who are better versed in the entire project, rather than just their section. It also helps keeps the project moving and eliminates wasteful time. The cross-functional approach correlates well with the cross-functional nature of MCE. The model-centric methodology requires all engineers—design, manufacturing, process, and quality—to be involved with every stage of the process (Renaissance, 2008).

Co-located cross-functional teams further enhance the time-to-market deduction, allowing companies to be more agile and quickly respond to customer demands by working concurrently (Montgomery & Levine, 1996). With all cross-functional team members operating from the same area, the product flow and quality is improved. This is once again due to increased communication, which results in quicker problem solving (Melsa, 1999). Similar to just-in-time manufacturing, this collocation of engineers can be referred to as cell-based (Sandras, 1989). Virtual collaboration (such as Internet, e-mail, and video conferencing) is an alternative to physical collaboration. But even though technology has opened the communication world to almost everyone, if the communication is not as instantaneous as tapping a person on the shoulder to get a response, time is wasted while waiting.

Decreasing the time-to-market also shortens the amount of time required from concept to production. As reviewed earlier within the model-centric section of this paper, the traditional design methodology is linear. See Figure 12 for the traditional design system flow.

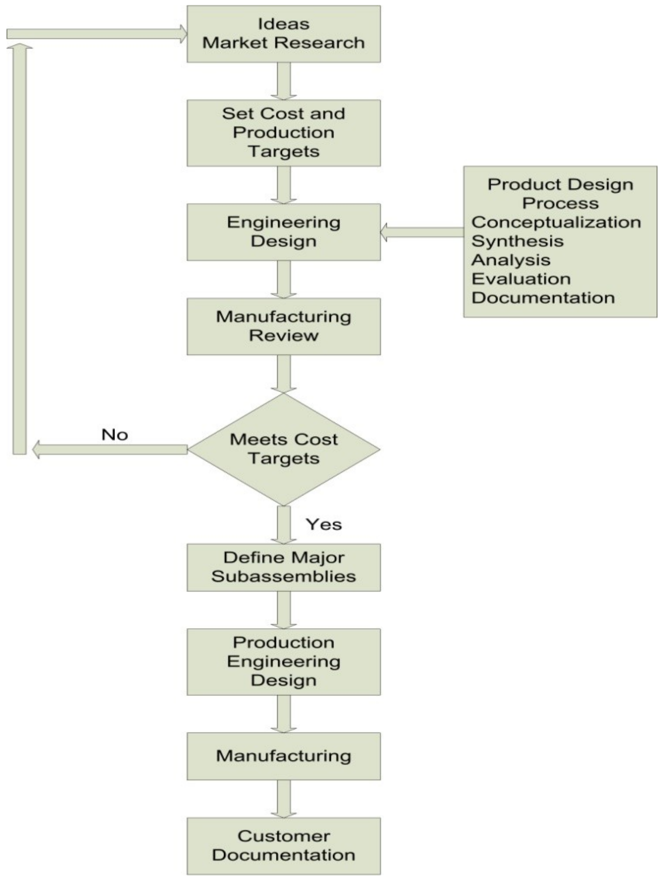

Figure 12. Traditional Design System Flow Chart

The next section of the design process can’t start until the previous one is complete. If any section runs into issues, then the whole remaining part of the chain is delayed, and the end production date is missed or postponed. Communication is also impeded because the data follows the process, rather than the process obtaining the data. This can cause miscommunication, resulting in design errors and costly rework. Process planning and tooling cannot start until the design is finished, which is complicated by the design engineer’s lack of ability to forecast design completion dates (Melsa, 1999). The result is a longer design cycle, wasted time, and an extended time-to-market.

Contrary to traditional design methodology, concurrent engineering does not limit the design process to design engineers. Rather, all parties have input across all areas of the product life cycle, from the initial design stage through manufacturing, servicing, and disposal (Rehg & Kraebber, 2005). Figure 13 illustrates the concurrent engineering flow (Rehg & Kraebber, 2005).

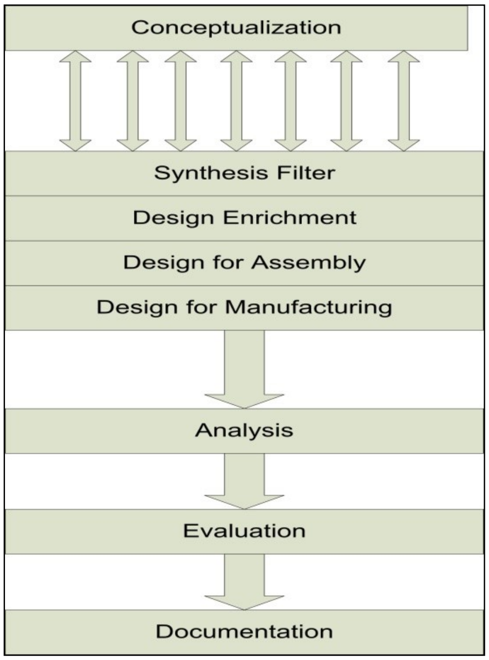

Figure 13. Concurrent Engineering Flow Chart

By utilizing concurrent engineering during process development, manufacturers can significantly improve time-to-market by reducing waiting time, while ensuring that the product meets the form, fit, and function requirements of the customer. Even though the design process may take longer and involve a larger team, the overall product development cycle is still shorter. Thus, the entire manufacturing process is ready sooner than it would be in the traditional design methodology. Table 3 illustrates more details on the benefits of concurrent engineering (Miller & Blanchard, 2004).

Table 3

Benefits of Concurrent Engineering

Benefits of CE from the start of Product Development	Percentage Change
Development Time	30% to 70% less
Engineering Changes	65% to 90% less
Time-to-Market Interval.	20% to 90% less
Overall Quality	200% to 600% higher
White-Collar Productivity	20% to 110% higher
Dollar Sales	5% to 50% higher
Return on Assets	20% to 120% less

There are many different approaches to incorporating concurrent engineering into the product development cycle. One popular approach was developed by James Nevins and Daniel Whitney of the Draper Laboratory, an independent not-for-profit laboratory in applied research. They created the following five-stage process as a generic template for any type of product manufacturing:

1. *Concept Phase*. In this phase, the product development team makes the major decisions concerning fit, form, and function. This phase accounts for 70% of the overall product cost and market impact.
2. *Major Subassembly Design Phase*. After the concept is approved in the concept phase, the team determines the major subassemblies and passes along the concept

for detailed engineering. At this point, the designers assess the feasibility of using modular and standard components to reduce cost.

3. *Single-Part Design Phase*. During this phase, all of the piece components and subassemblies are designed. Changes at this phase have tremendous impact on schedule.
4. *Design of Part-Pairs Phase*. In this phase, the engineers review the interaction of individual part design for proper fit and manufacturability. This involves assessing geometric dimensioning and tolerances along with testing and acceptance criteria.
5. *Grouping of Parts and Subassemblies*. In this final phase, the engineers review all piece components and subassemblies for efficient assembly methods and sequence. Tooling and equipment are also designed and procured for manufacturing.

Although product teams now use cross-functional design, MCE, and concurrent engineering to improve product development, these methods do not necessarily guarantee shorter time-to-market. The key is discovering how best to utilize these methods to solve for wasted product development time. It does not depend the phase of a product's development; any time that is not spent pushing the product closer to market equals valuable time and money wasted.

By integrating all product information into a centralized model, MCE facilitates concurrent engineering, design for six sigma, design to cost, and design for manufacturing—all of which save valuable time (Renaissance, 2008). MCE's shared database is particularly critical for the implementation of concurrent engineering because it allows every individual and team involved to closely follow the product through design, manufacturing, and final production.

When concurrent engineering is not used, companies are more likely to require engineering changes to correct design problems found during the manufacturing phase (Walker & Cox, 1999).

Table 4

Common Time-Wasting Production Issues

Phase	Time-Wasting Production Issues
Entire Project	• Front-end errors, resulting in change and waste down stream • Unclear feature definitions or definition change • Lack of appropriate skills and training • Feature creep • Movement of people to other projects • Technological problems • Functional specification and design errors • Regulatory requirements
Front-End Phase	• Omission of "need" and "ready to investigate" time requirements • Part-time marketing staff • Insufficient staff for project stage • Small per-month expenses
Development Phase.	• Simultaneous technological development • Loosely defined product definition • Lack of system architecture and requirement documentation • Last-minute regulatory problems holding up manufacturing • Unscheduled hardware and software revisions • Multi-version software requirements demanding multiple integration cycles
Deployment Phase	• Long customer evaluation intervals • Resulting customer demand changes • Ramp-up limitations due to insufficient manufacturing implementation plans

Summary

In order to be competitive in today's global market, manufacturing firms must decrease their time-to-market and increase their ability to meet ever-changing customer needs. The MCE is an approach that may make it easier for firms to quickly respond, thus meeting both of these global market demands. This is accomplished through the use of a model-centric database. Such a database remedies the issues associated with traditional manufacturing's multiple databases by providing a centralized, engineer-based tool for inputting and gathering all design, manufacturing, and inspection data (Walker & Cox, 1999).

As the need to respond to evolving customer demands continues to grow, companies are building new product development teams with the skills and tools to support that need (Coffin & Allen, 2008). With MCE, these companies increase the capabilities of their concurrent engineering teams, thus reaching across organizational and geographical boundaries to meet more requirements from more customers (O'Connor & Rasdorf, 1998).

Whether or not a company succeeds in manufacturing a quality product is closely related to the way it designs, prototypes, and processes its product parts (Walker & Cox, 1999). With solid modeling and its related tools, companies can now produce higher quality results at each stage of manufacturing, while decreasing both time-to-market and customer response time in the process (Musto, Howard, & Rather, 2004). Therefore, manufacturers are finding that MCE technologies help meet not only changing market demands, but also the traditional market needs of high quality and efficiency.

From the literature review, MCE is defined as the methodology of utilizing a three-dimensional, computer-generated model as the center of the design and manufacturing phase of a product life cycle. This three-dimensional model serves as the single source to digitally contain all product information, from design through process development. By utilizing engineering and manufacturing software, product designers can effectively analyze data and develop processes to simulate and expedite the product design cycle. Concurrent engineering—in conjunction with CAD, CAE, and CAM—provides the organizational structure for teamwork and communication to compliment the capabilities of MCE software tools. The intended benefit of utilizing MCE is to reduce time-to-market and accommodate customer-required changes through consistent, parallel communication that facilitates design and manufacturing analyses from the beginning of a product's development cycle.

The literature review revealed the following key factors affecting MCE's degree of success:

- Issues implementing or sustaining MCE.
- Level of experience with CAD, CAE, and CAM.
- Types of software used.
- Job functions within the product development process.
- Location of engineering functions.
- Complexity of the design model.
- Time-to-market.
- Ability to accommodate change, defined by time.

The literature review provided knowledge of the MCE methodology and assisted the researcher in developing a definition of MCE for use in this study. The review defined key characteristics of MCE for use in performing a comparative study on the utilization of MCE as it relates to manufacturing competitiveness. The key factors listed above were then used to develop and administer a research survey to a sample of manufacturing firms and gather research data.

Analysis from this data was utilized to address the research questions and provide a conclusion on the study's research problem. The research methodology to address the problem of this study is presented in Chapter 3.

CHAPTER 3

METHODOLOGY

The purpose of this study was to investigate the relationship between the use of model-centric engineering and a firm's competitiveness as defined by time-to-market and agility to accommodate customer-required changes. The study focused on two areas. The first area of focus was to define the current model-centric environment in the manufacturing industry by factors such as level of usage, years of experience, and discrete job functions of employees utilizing MCE, and issues. The second area of focus concentrated on the relationship between MCE use and company competitiveness. This relationship involved comparing a firm's level of MCE usage to the firm's time-to-market, agility to accommodate customer-required changes and company sales. The following research questions are individually addressed in Chapter 4 using data gathered from the industry survey developed by the researcher. The industry survey was developed from possible influential factors of MCE uncovered by the researcher's literature review and validated from a group of subject matter experts in the field of MCE.

Research Questions

Research Question 1: What is the average level of MCE utilization among manufacturing firms?

Research Question 2: What types of MCE implementation and utilization issues do manufacturing firms encounter?

Research Question 3: Is there a relationship between the sizes of manufacturing firms due to the implementation of MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 4: Is there a relationship between manufacturing firms with or without discrete job functions of employees utilizing MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 5: Is there a relationship between manufacturing firm's experience levels of MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 6: Is there a relationship between manufacturing firm's engineering groups that are or are not co-located and the initial time-to-market and agility to accommodate customer-required change?

Research Question 7: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on initial time-to-market?

Research Question 8: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on agility to accommodate customer-required change?

Research Question 9: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, engineering location, software implementation, and MCE experience level on company sales?

The following hypothesis statements were developed from these research questions. These hypotheses were individually tested through statistical analysis in Chapter 4 and analyzed utilizing data gathered from an industry survey developed by the researcher utilizing specific statistical techniques under the assistance of the Bowling Green State University Research Department. Demographic data from the industry survey addressed Research Questions 1 and 2, while the following null and alternative hypothesis addressed Research Questions 3 though 9.

1. H_{01}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the size of a manufacturing firm.

   H_{A1}: $\Theta \neq 1$. There is a statistically significant relationship between the initial time-to-market and the size of a manufacturing firm.

2. H_{02}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

   H_{A2}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

3. H_{03}: $\Theta = 1$. There is no statistically significant relationship between the initial time-to-market and discrete MCE job functions.

   H_{A3}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and discrete MCE job functions.

4. H_{04}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

   H_{A4}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

5. H_{05}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

   H_{A5}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

6. H_{06}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

   H_{A6}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

7. H_{07}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

   H_{A7}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

8. H_{08}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

   H_{A8}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

9. H_{09}: $\beta_j = 0$. There is no statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

H_{A9}: $\beta_j \neq 0$. There is a statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

10. H_{010}: $\beta_j = 0$. There is no statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

    H_{A10}: $\beta_j \neq 0$. There is a statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

11. H_{011}: $\beta_j = 0$. There is no statistically significant relationship between company sales and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

    H_{A11}: $\beta_j \neq 0$. There is a statistically significant relationship between company sales and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Population

The population of this study focused on the Transportation Equipment Manufacturing Sector Code number 336 defined by the North American Industry Classification System

(NAICS). The NAICS was developed by the United States, Canada, and Mexico to create a uniform classification system for North American industries. This industry classification system enables North American Free Trade Agreement (NAFTA) partners—the United States, Canada, and Mexico—to better compare economic and financial statistics, ensuring that such statistics keep pace with the changing economy (Census Bureau, 2007).

Industries in the Transportation Equipment Manufacturing Code number 336 produce equipment for transporting people and goods. Firms in this subsector utilize production processes, such as bending, forming, welding, machining, and assembling metal or plastic parts into components and finished products. This classification includes the following industries, but it does not include agricultural, construction, or material handling equipment.

- Automotive.
- Light and Heavy Duty Trucks.
- Motor Homes and Trailers.
- Aircraft.
- Space Vehicles and Propulsion.
- Railroad.
- Ship and Boat.
- Motorcycle.
- Defense Vehicles and Guided Missiles.

This classification applied to 11,767 establishments in the United States in the 2007 census. *Establishment* was defined as a single physical location at which business was conducted or services provided. A firm could have more than one establishment, in which case a larger company may have more than one representative taking part in the survey. The amount of sales, shipments, receipts, revenue, or business reported for this classification (including domestic establishments) equaled $736 billion per year (Census Bureau, 2007).

The total number of paid employees in 2007, in the NAICS code 336 classifications, equaled 1,548,327. This included all permanent full-time and part-time noncontract employees who worked or received pay for any part of that pay period (Census Bureau, 2007). The annual total payroll of NAICS code 336 establishments in 2007 was $85 billion (Census Bureau, 2007). This study included the population of 1,548,327 individuals, representing 11,767 establishments of the NAICS code 336 classifications. This group of individuals is referred to as the Transportation Equipment Manufacturing Sector.

Sample

The sample of the population for this study was extracted from the Society of Manufacturing Engineer's (SME) member database. SME classifies their members by a variety of categories, such as profession, company size, and special classifications such as the NAICS. The Society of Manufacturing Engineers has 24,878 members that are categorized under the NAICS Transportation Equipment Manufacturing Sector code 336.

A sample size of 267 was needed to satisfy a margin of error assumption of 5% and a confidence level of 95% for the study. Due to the purchasing constraints of SME, the sample of 3,000 individuals was chosen for this study because this was the minimum number of contacts required for purchase. In addition, Internet surveys average a 13.35% complete return rate (Hamilton, 2009). With an expected return rate of 13.35%, the sample size predicted a return equal to 400 respondents. It was 133 more respondents than needed for the study's sample size.

The SME sales consultant used their member database to generate a random sample contact list. This list was used by the SME sales consultant both to identify the recipients of the researcher's cover letter and the survey that asked for survey participation. The SME sales consultant generated a contact list of 3,250 members that match the category of NAICS transportation equipment manufacturing sector code number 336. An additional 250 contacts also were included in the survey to supplement contacts that were chosen, but the contact information is no longer valid. The SME contact list of the 3,250 names and their contact information were never shared with the researcher, thus keeping the list anonymous.

Variables

The variables listed below were derived from the literature review concerning MCE. There were 19 independent and 3 dependent variables, which were used to develop the industry survey.

Independent Variables

- Profession – Categorical.
- Job Responsibility – Categorical.
- Manufacturing Firm Size – Categorical.
- Education Level – Categorical.
- NIACS Classification – Categorical.
- Production Rate – Categorical.
- Throughput Time – Categorical.
- Product Complexity Level – Categorical.
- Quantity of Design Changes – Continuous.
- Quantity of Problem Reports – Continuous.
- Quantity of Engineers – Categorical.
- Engineering Location – Categorical.

- Design Data Storage – Categorical.
- MCE Job Functions – Categorical.
- Types of Software – Categorical.
- MCE Training – Categorical.
- Experience with MCE – Continuous.
- Quality of MCE– Categorical.
- Level of MCE Practice – Categorical.

Dependent Variables

- Time-to-market – Continuous.
- Agility To Accommodate Customer-Required Changes – Continuous.
- Company Sales – Continuous.

Survey Development and Validation

An industry survey was developed by the researcher to collect data regarding MCE. The basis of the survey was structured from the researcher's literature review identifying and defining key independent and dependent variables. These key variables listed in the variable section of this study were identified because of their potential to affect the relationship between MCE and a firm's competitiveness.

An initial draft of the survey questions and its corresponding categorical responses were developed. The questions focused on capturing information on the respondent, the company, the use of MCE, and the issues with MCE. The initial set of survey questions were distributed to a panel of six subject-matter experts in the field of MCE. This panel consisted of two college professors who perform research and teach model-based methods, one model- based engineering consultant, and three professional engineers who have MCE degrees. The panel was asked to review the relevancy of the questions along with the validity of the categories for each question. The panel was given one week for the review and was asked to return any comments to the researcher. The comments and suggestions were evaluated and incorporated into the survey. The survey was again distributed to the panel for a final review. The panel had an additional week for the final review and was asked to return any further feedback for the survey. The researcher finalized the survey consisting of 24 multiple-choice questions and one data input question.

The researcher created a cover letter communicating the key elements of the survey to the potential respondents (See Appendix B). This included identifying the researcher and the purpose of the survey regarding MCE and the possible relationship to time-to-market and the ability to accommodate customer-required changes. The cover letter also addressed the respondent's risk, benefits, and rights for being involved with the MCE survey. This included the statements of confidentiality for the respondents and that the survey was completely voluntary. The cover letter also explained that the survey was reviewed by the Indiana State University Institutional Review Board (IRB). Finally the cover letter gave the respondents a choice to continue with the survey or exit if not interested. The survey and the cover letter were then combined to create the final content for the survey instrument.

The researcher used "surveymonkey" software and collection services to formalize the industry survey into an Internet-based survey. This included a web address link that was attached to the respondents' survey invitation. The final complete survey instrument can be found in Appendix C of this study. The completed industry survey along with the university IRB request forms were then submitted to the Institutional Review Board from Indiana State University. The MCE industry survey (IRB# 10-155) was deemed exempt from oversight of the

Human Subjects Board from Indiana State University, which allowed the researcher to administer his survey to the previously identified sample.

Survey Implementation

The researcher purchased an anonymous contact list from the Society of Manufacturing Engineers. This contact list consisted of 3,250 individuals from the transportation equipment manufacturing sector code number 336, as defined by the NAICS. The researcher provided the SME consultant with an introductory electronic mail invitation asking the respondents to participate in the MCE survey. This survey invitation can be found in Appendix A of this study. The invitation included a linked web address, which directed the respondents to the survey. The SME consultant created the formal invitation that would be delivered from SME to the respondents. This formal invitation was then sent to the researcher to verify the invitation was correct and the linked web address functioned correctly to open and complete the survey. The researcher then provided SME the survey invitation approval and allowed SME to distribute the survey to the randomly sampled contact list. Three days after the first distribution, SME distributed the survey invitation a second time to increase the response rate. A third attempt and final attempted to distribute the survey by SME occurred fourteen days after the initial distribution of the survey. The survey was administered through SME, and at no time did the researcher have contact with any survey participants.

Statistical Analysis

By analyzing descriptive statistics of the survey data, demographics of the sample were determined. This background information was intended to answer Research Question 1 concerning the average level of model-centric utilization among companies. Likewise, using the descriptive data from the survey, the researcher categorized common issues with MCE and provided descriptive statistical analysis to answer Research Question 2.

Research Questions 3-6 were answered utilizing analysis of contingency tables and Fisher's exact test of significance. Fisher's exact test of significance was used instead of Chi-square because of the study's small sample size.

Assumptions for utilizing the Fisher's exact test for significance were:

- Data was randomly sampled.
- Directional hypothesis.
- Independent observations.
- Dichotomous level of measurement.

This method allowed the researcher to test:

- The relationship between time-to-market and agility to accommodate customer-required changes to the size of a manufacturing firm.
- The relationship between time-to-market and agility to accommodate customer-required changes when compared to whether or not a firm has discrete MCE job functions.
- The relationship between time-to-market and agility to accommodate customer-required changes when compared to MCE experience level.
- The relationship between time-to-market and agility to accommodate customer-required changes when compared to whether or not a firm's engineering group is co-located.

The answers to Research Questions 7-9 are derived from logistic regression analysis, which models the relationship between a single dependent variable and a set of independent variables. This type of analysis is used to determine factors that affect the presence or absence of a characteristic when the dependent variable has three or more levels.

Logistic regression allows one to predict a discrete outcome from a set of variables that may be continuous, discrete, dichotomous, or a mixture of all. The dependent variable in logistic regression is usually dichotomous, that is, the dependent variable can take the value 1 with a probability of success θ, or the value 0 with probability of failure 1-θ.

As mentioned previously, the independent or predictor variables in logistic regression can take any form. That is, logistic regression makes no assumption about the distribution of the independent variables. They do not have to be normally distributed, linearly related, or of equal variance within each group. The relationship between the predictor and response variables is not a linear function in logistic regression; instead, the logistic regression function is used, which is the logit transformation of θ: (Hosmer & Lemeshow, 2000).

Logistic regression equation:

$$\mathbf{logit}\left[\theta(\mathbf{x})\right] = \mathbf{log}\left[\frac{\theta(x)}{\mathbf{1}-\theta(x)}\right] = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i$$

Figure 14. Logistic Regression Equation

Logistic regression analysis allows the researcher to model the relationship between:

- The dependent variable of time-to-market as it relates to the independent variables of MCE practice, manufacturing firm size, discrete MCE job functions, production volume, engineering location, software implementation, and MCE experience.
- The dependent variable of agility to accommodate customer-required changes as it relates to the independent variables of MCE practice, manufacturing firm size,

discrete MCE job functions, production volume, engineering location, software implementation, and MCE experience.

- The dependent variable of trends in market sales as it relates to the independent variables of MCE practice, manufacturing firm size, discrete MCE job functions, production volume, engineering location, software implementation, and MCE experience.

The survey design and statistical data analysis were overseen by the Bowling Green State University Statistical Laboratory to ensure an in-depth and accurate study. SAS statistical software was utilized to analyze the survey data presented in Chapter 4.

Summary

The purpose of this study was to determine if MCE affects a firm's competitiveness, as defined by time-to-market and agility to accommodate customer-required changes, by improving customer satisfaction. The study was focused on two areas. The first defined the current model-centric environment in the manufacturing industry by factors, such as level of usage, years of experience, and discrete job functions of employees utilizing MCE and usage. The second concentrated on the relationship between MCE utilization and company competitiveness. This involved comparing a firm's level of MCE usage to the firm's time-to-market, agility to accommodate customer-required changes, and company sales. Results from this study provided a current quantitative representation based upon an industry survey of MCE's relationship to the success of a manufacturing firm within its given industry.

Throughout the development and implementation of the industry survey, data was gathered for statistical analysis. Frequencies and percentages were developed for each survey question to describe the responses. Similarly, contingency tables were created and analyzed utilizing Fisher's exact test of significance for hypothesis testing determining relationships between the study's identified variables. Logistic regression analysis was utilized to model the relationship between the dependent variables of time-to-market, agility to accommodate customer-required changes, and company sales to the independent variables of MCE practice, manufacturing firm size, discrete MCE job functions, production volume, engineering location, software implementation, and MCE experience. The statistical analysis as described in this section is presented in Chapter 4 of this study.

CHAPTER 4

RESULTS

The purpose of the study was to determine if MCE affects a firm's competitiveness, defined by time-to-market and agility to accommodate customer-required changes for customer satisfaction. Through the use of the research survey defined in Chapter 3, data was collected to address the outlined research questions from Chapter 1. In this chapter the data was presented and analyzed in two separate sections. The first section provided descriptive statistics on each of the survey questions. The second section provided data analysis and hypothesis testing for each of the nine research questions respectively.

The following is a review of the identified research questions pertaining to this study.

Research Question 1: What is the average level of MCE utilization among manufacturing firms?

Research Question 2: What types of MCE implementation and utilization issues do manufacturing firms encounter?

Research Question 3: Is there a relationship between the sizes of manufacturing firms due to the implementation of MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 4: Is there a relationship between manufacturing firms with or without discrete job functions of employees utilizing MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 5: Is there a relationship between manufacturing firm's experience levels of MCE and the initial time-to-market and agility to accommodate customer-required change?

Research Question 6: Is there a relationship between manufacturing firm's engineering groups that are or are not co-located and the initial time-to-market and agility to accommodate customer-required change?

Research Question 7: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on initial time-to-market?

Research Question 8: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level on agility to accommodate customer-required change?

Research Question 9: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, engineering location, software implementation, and MCE experience level on company sales?

The following hypothesis statements were developed from these research questions and analyzed utilizing data gathered from the industry survey. Statistical assistance was provided to the researcher by Bowling Green State University Research Department with specific statistical techniques. Demographic data and descriptive statistics from the industry survey addressed

Research Questions 1 and 2 while the following null and alternative hypothesis addressed Research Questions 3 though 9.

1. H_{01}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the size of a manufacturing firm.

   H_{A1}: $\Theta \neq 1$. There is a statistically significant relationship between the initial time-to-market and the size of a manufacturing firm.

2. H_{02}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

   H_{A2}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

3. H_{03}: $\Theta = 1$. There is no statistically significant relationship between the initial time-to-market and discrete MCE job functions.

   H_{A3}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and discrete MCE job functions.

4. H_{04}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

   H_{A4}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

5. H_{05}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

   H_{A5}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

6. H_{06}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

   H_{A6}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

7. H_{07}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

   H_{A7}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

8. H_{08}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

   H_{A8}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

9. H_{09}: $\beta_j = 0$. There is no statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

   H_{A9}: $\beta_j \neq 0$. There is a statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

10. H_{010}: $\beta_j = 0$. There is no statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.
    H_{A10}: $\beta_j \neq 0$. There is a statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.
11. H_{011}: $\beta_j = 0$. There is no statistically significant relationship between company sales and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.
    H_{A11}: $\beta_j \neq 0$. There is a statistically significant relationship between company sales and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Survey Participation

The research survey pertaining to MCE was distributed as described in Chapter 3. The survey was delivered by electronic mail to 3250 NAICS Transportation Equipment Manufacturing Sector 336 contacts by SME. Out of the 3250 electronic mail distributions, 2,932 messages were delivered successfully. The other 318 messages were returned to SME as not delivered because of invalid or outdated contact information. The rate of the successful delivery of the survey equaled 90%. Of the 2,932 contacts, 454 opened the survey link to review the survey information. The actual acknowledgment rate for the survey equaled 15%. Out of the 454 contacts that opened the link, 59 individuals responded to the survey creating a response rate of 13% of the surveys that were acknowledged. The overall response rate of the successfully delivered surveys, including the emails in which the survey was not acknowledged, equaled 2%.

The sample size of 59 respondents fell short of the required 267 respondents to satisfy a margin of error assumption of 5% and a confidence level of 95% for the study. Having 59 respondents rather than the 267 required respondents for the study's sample changed the margin of error assumption from 5% to 12.74 %. The confidence level remained 95%. Because the number of respondents did not meet the required sample size for the study, it is unsure if the respondents who answered the survey truly represent the population of the NAICS Transportation Equipment Manufacturing Sector code 336.

Survey Results

In this first section, the survey response data is presented in table format for each survey question. Each set of data was analyzed to determine the percentage and frequency of the responses for each survey question.

Survey Question 1 – What is your profession?

Table 5

Profession

Profession Type	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Engineer	43	72.88	43	72.88
Production Foreman	1	1.69	44	74.58
Operations Manager	4	6.78	48	81.36
Company Executive	6	10.17	54	91.53
Other	5	8.47	59	100.00

59 survey respondents participated in this question

In question 1 the profession of the individuals who participated in the survey was determined. The survey results for Question 1 are illustrated in Table 5. The majority of the respondents, 72.88%, classified themselves as engineers. Another 18.64% of the respondents indicated that their profession was management related. This included the classifications of Production Foreman, Operations Manager, and Company Executive. The remaining 8.47% of the respondents provided an "other" response, indicating that they did not fit the engineer or a management classification. Thus the majority of the respondents for this survey were engineers. This is logical due to the list of surveyed respondents being derived from the SME contact database whose majority of the members, even though not limited too, are engineers.

Survey Question 2 – What is your job responsibility?

Table 6

Responsibility

Job Responsibility	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Product Design	12	20.34	12	20.34
Process Design	22	37.29	34	57.63
Management	7	11.86	41	69.49
Production	11	18.64	52	88.14
Other	7	11.86	59	100.00

59 survey respondents participated in this question

The respondents were asked in Questions 2 what was their core job responsibility within their firm. The survey results for Question 2 are illustrated in Table 6. Process design as a core job function had the highest percentage of respondents with 37.29%. This was followed by product design and production at 20.34% and 18.64% respectively. Management job responsibilities corresponded to 11.86% of the responses. Also, 11.86% of the respondents' job responsibilities were assumed neither engineering nor management related. The responses for Question 1 and Question 2 do not correlate. For instance Question 1 stated 18.64% of the respondents fell into a management classification whereas Question 2 indicated 11.86% of the respondents have a management job function. This inconsistency is assumed to be because the respondents' response for Question 1 reflected job title while their response on Question 2 reflected their actual job function that they are performing within their firm.

Survey Question 3 – What is your highest level of college education?

Table 7

Education Level Earned

Highest College Level	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	5	8.47	5	8.47
Certificate	1	1.69	6	10.17
Associate	8	13.56	14	23.73
Bachelor	28	47.46	42	71.19
Master	14	23.73	56	94.92
Doctorate	3	5.08	59	100.00

59 survey respondents participated in this question

In Question 3 the respondents were asked what was their highest level of college education. The survey results for Question 3 are illustrated in Table 7. Per the survey results, 76.27% of the respondents had either a Bachelor and/or advanced degrees. The respondents who had post high school training of some type equaled 91.53%. This question confirms educational level of the sample, but it does not specify what their education pertained to or if it was directly or indirectly relevant to the subject of this study.

Survey Question 4 – What is your company size?

Table 8

Company Size

Number of Employees	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1 to 499 Employees	30	50.85	30	50.85
500 to 2499 Employees	11	18.64	41	69.49
Greater than 2500 Employees	18	30.51	59	100.00

59 survey respondents participated in this question

For Question 4 the respondents were asked what is their company size based on employee population size. Table 8 illustrates the survey results related to question 4. The responses of the survey provided that 50.85% of the respondents were employed with companies who had less than 500 employees, whereas the remaining 49.15% were from companies with employment size greater than 500 employees. Of the 49.15% of companies with employment size greater than 500 employees, 30.51% of the respondents worked for a firm who employed 2,500 or more individuals. The responses for this question are somewhat equally distributed over small (1-499 employees) and large (greater than 500 employees) firms based on the number of employees.

Survey Question 5 – What is your company's estimated average annual total sales?

Table 9

Company Sales

Company Sales	Frequency	Percent	Cumulative Frequency	Cumulative Percent
$0 to $100 Million	24	40.68	24	40.68
$100 to $400 Million	10	16.95	34	57.63
Greater than $400 Million	24	40.68	58	98.31
Unknown	1	1.69	59	100.00

59 survey respondents participated in this question

The respondents were surveyed in Question 5 related to their employer's average annual total sales. The survey results for Question 5 are illustrated in Table 9. The two largest categories consisted of average annual total sales of less than $100 million and greater than $400 million. Both of these categories included 40.68 % of the respondents. A smaller percentage of the respondents, 16.95%, fell in the sales category of $100 million to $400 million. The responses to this survey question were somewhat equally distributed over the three categories representing total sales. Even though one respondent selected unknown in the survey relating to the company sales, this response had little effect on the other survey data.

Survey Question 6 – What North American Industry Classification System (NAICS) group does your company belong to?

Table 10

NAICS Group Classification

NIACS Group	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Motorcycle	3	5.08	3	5.08
Automotive/Truck	18	30.51	21	35.59
Aerospace/Missile	23	38.98	44	74.58
Locomotive	1	1.69	45	76.27
Ship/Boat	1	1.69	46	77.97
Military Armor Vehicle	7	11.86	53	89.83
Unknown	6	10.17	59	100.00

59 survey respondents participated in this question

In Question 6 the survey respondents were asked what North American Industry Classification System (NAICS) group is their company categorized as. Table 10 displays the survey results for Question 6. The aerospace and missile category contained the majority, 38.98%, of the surveyed responses. The second largest grouping was the automotive and truck category. This category contained 30.51% of the surveyed responses. Another 11.86% of the respondents selected military armor vehicles as their NAICS group. These three categories of NAICS collectively represented 81.35% of the responses for Question 6. The other three distinct groups consisting of motorcycle, ship and boat, and locomotive had minimal representation within the survey, that is, it had only 5 of the 59 respondents. The other 6 of the 59 total respondents were unsure of their firm's group because they indicated their firm serves within multiple NAICS code 336 groups.

Survey Question 7 – What is your company's typical production rate for your primary product?

Table 11

Typical Production Rate

Production Rate	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Individual/Custom Build	6	10.17	6	10.17
1 to 10 Products per Year	4	6.78	10	16.95
1 to 10 Products per Month	5	8.47	15	25.42
1 to 10 Products per Week	8	13.56	23	38.98
1 to 10 Products per Day	7	11.86	30	50.85
Greater than 10 Products per Day	29	49.15	59	100.00

59 survey respondents participated in this question

In Question 7 the survey respondents were asked what the typical production rate was for their firm. The greatest number of responses was attributed to the greater than 10 products per day category. This category equaled almost half, 49.15%, of the responses. The responses for the other 5 categories collectively represented the other half, 50.85%, of the respondents. The complete survey results for Question 7 are illustrated in Table 11.

Survey Question 8 – What is the manufacturing throughput time of your primary product?

Table 12

Manufacturing Throughput Time

Time	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Less than 1 Month	24	40.68	24	40.68
1 to 2 Months	14	23.73	38	64.41
3 to 6 Months	13	22.03	51	86.44
Greater than 6 Months	8	13.56	59	100.00

59 survey respondents participated in this question

The survey respondents in Question 8 were asked what their typical throughput time was for their primary product. The survey results for Question 8 are illustrated in Table 12. The highest percentage (40.68%) of the respondents reported throughput time of less than 1 month. Just over 20% of the respondents reported a throughput time of each 1 to 2 months and 3 to 6 months, 23.73% and 22.03% respectively. Throughput time of 6 months or greater represented 13.56% of the population. The majority of the respondents were able to produce their product from the manufacturing order to product delivery within a 6-month time frame. This is reasonable since almost 50% of the respondent's average a daily product rate of 10 products were referenced in Question 7. If throughput time was greater for a high product rate, more manufacturing resources such as space and tooling would be needed to accommodate the rate.

Survey Question 9 – Describe the level of complexity of your primary product by the following?

Table 13

Product Complexity Level

Product Complexity	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Complete Vehicle Assembly & Integration	17	28.81	17	28.81
Major and Minor Sub-Assembly Build	22	37.29	39	66.10
Single Component or Piece Parts	20	33.90	59	100.00

59 survey respondents participated in this question

This question surveyed the respondents to rate the complexity level of their product. The survey results for Question 9 are illustrated in Table 13. The responses to this question were evenly distributed over the three categories, with sub-assembly being the highest at 37.29%. The responses to this question illustrates that the surveyed respondents represent firms that not only represent the single piece manufacturing but also the complete vehicle build production.

Survey Question 10 – What is your company's average time from beginning of product concept stage to market delivery?

Table 14

Time-to-Market

Time	Frequency	Percent	Cumulative Frequency	Cumulative Percent
0 to 6 Months	13	22.03	13	22.03
6 Months to 1 Year	10	16.95	23	38.98
1 to 2 Years	22	37.29	45	76.27
2 Years or More	14	23.73	59	100.00

59 survey respondents participated in this question

In Question 10 the respondents were asked to classify their firm’s average time from beginning of product concept stage to market delivery. From the responses, 37.29% of the respondents indicated their time-to-market ranged from one to two years. The remaining three categories were close in percentages ranging from 16.95% to 23.75%. By dividing the categories into two groups, 61.02% of the responses indicated greater than one year time-to-market. The remaining 38.98% would have a time-to-market of less than one year. Overall the responses represented the entire range of the survey categories. Table 14 displays the complete results of Question 10.

Survey Question 11 – What is the average time from an initial customer request to begin production?

Table 15

Time for Customer Change Request

Time	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Less Than 1 Month	7	11.86	7	11.86
1 to 2 Months	10	16.95	17	28.81
3 to 6 Months	16	27.12	33	55.93
Greater Than 6 Months	26	44.07	59	100.00

59 survey respondents participated in this question

In Question 11 of the survey the respondents were asked to classify their firm's average time from initial customer request to the beginning of product manufacturing. The survey results for Question 11 are illustrated in Table 15. The survey results illustrate that 44.07% of the respondents indicated their time from an initial customer request to the beginning of product manufacturing was greater than 6 months. Another 27.12% of the respondents noted that it took 3 to 6 months to react to a customer change request, whereas 16.95% of the respondents noted it took 1 to 2 months. If the categories were divided into two groups, 55.93% of the responses indicated less than 6 months reaction time to customer change and the remaining 44.07% would have a reaction time of greater than 6 months. Overall the responses represented the entire range of the surveyed categories.

Survey Question 12 – How many design changes, on average, occur between the concept stage and market delivery?

Table 16

Number of Design Changes

Quantity of Design Changes	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Less Than 15	23	38.98	23	38.98
15 to 25	12	20.34	35	59.32
25 to 50	4	6.78	39	66.10
Greater Than 50	20	33.90	59	100.00

59 survey respondents participated in this question

For Question 12 the respondents were surveyed pertaining to the number of design changes occurring between the concept stage and market delivery. The survey results for Question 12 are illustrated in Table 16. From the survey results, 38.98% of the respondents indicated that less than 15 changes occur between concept and the time it takes to get the product to market. In contrast, 33.90% of the respondents said greater than 50 design changes occur during this same timeframe. If the middle two classifications were combined, 27.12% of the respondents have 15 to 50 design changes from concept through market delivery. Even though the classification for less than 15 requested design changes had the highest percentage of respondents, 38.98%, the majority of the respondents had an average of 15 or greater requested design changes that occur between the concept stage and market delivery. These responses were relatively distributed among the three categories that were classified as 15 design changes or greater.

Survey Question 13 – How many problem reports or corrective actions on average occur between the concept stage and market delivery?

Table 17

Number of Problem Reports

Quantity of Problem Reports	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Less Than 15	27	45.6	27	45.76
15 to 25	7	11.86	34	57.63
25 to 50	10	16.95	44	74.58
Greater Than 50	15	25.42	59	100.00

59 survey respondents participated in this question

In Question 13 the respondents were to select the number of problem reports or corrective actions that occurred between the concept stage and market delivery. Table 17 illustrates the results related to Question 13. Regarding the survey results, 45.60% of the respondents indicated that there are less than 15 problem reports or corrective actions that occur. In contrast 25.42% of the respondents said that greater than 50 problem reports or corrective actions occur during this same timeframe. Similar to Question 12, if the middle two classifications are combined, 28.81% of the respondents have 15 to 50 problem reports or corrective actions from product concept to market delivery. Even though the classification for less than 15 problem reports response had the highest percentage of respondents, the majority of the respondents had an average of 15 or greater problem reports or corrective actions that occur between the concept stage and market delivery. These responses are fairly equally distributed among the three categories that are included within the classification of 15 or more problem reports or corrective actions.

Survey Question 14 – How many Design Engineers are within your company?

Table 18

Number of Design Engineers

Quantity of Design Engineers	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	5	8.47	5	8.47
1 to 19	24	40.68	29	49.15
20 to 99	13	22.03	42	71.19
100+	17	28.81	59	100.00

59 survey respondents participated in this question

For Question 14 the respondent was to select the number of design engineers the respondent's firm employs. The survey results for Question 14 are illustrated in Table 18. From the survey data, 40.68% of the respondents respond that they have at least 1 design engineer and less than 20. Another 22.03 % respondents indicate that they have 20 to 99 design engineers. The respondents (28.81%) indicate that they have over 100 design engineers in their firm's employment. Lastly 8.47% of the respondents responded that they have no distinct design engineering position. Overall, excluding the 5 respondents who have no design engineering, the survey sample represented the three populated design engineer categories.

Survey Question 15 – How many Manufacturing / Process Engineers are employed within your company?

Table 19

Number of Manufacturing / Process Engineers

Quantity of Engineers	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	3	5.08	3	5.08
1-19 Manufacturing / Process	31	52.54	34	57.63
20-99 Manufacturing / Process	11	18.64	45	76.27
100+ Manufacturing / Process	14	23.73	59	100.00

59 survey respondents participated in this question

The respondents were asked in Question 15 to select the firm's number of manufacturing and process engineers. The survey results for Question 15 are illustrated in Table 19. Responses are similar to Question 14 regarding the number of design engineers. From the survey data, 52.54% of the respondents responded that they have at least 1 manufacturing or process engineer but less than 20. Another 18.64 % of the respondents indicated that they have 20 to 99 manufacturing and process engineers. The greater than 100 manufacturing and process engineer's category received 23.73% of the survey responses for this survey question. Lastly, 5.08% of the respondents responded that they have no distinct manufacturing or process engineer positions.

Survey Question 16 – Describe the physical locations of your Design and Manufacturing Engineering departments.

Table 20

Location of Design and Manufacturing / Process Engineers

Location	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Co-located, same building	27	45.76	27	45.76
Same facility, different building	12	20.34	39	66.10
Same company, different facility	15	25.42	54	91.53
Different company, different facility	5	8.47	59	100.00

59 survey respondents participated in this question

In Question 16 the respondents were to describe their engineering department's physical location within their firm. The survey results for Question 16 are illustrated in Table 20. The survey results show that 45.76% of the respondents indicated that their design and manufacturing engineering groups are collocated in the same building. Conversely, 20.34% responded that their engineers are in the same facility but different buildings within the facility. The survey data indicates that 33.89% of the respondents indicated that their engineering groups are not physically located within close location of each other because of their location being in a different facility or outside contracted. The responses provided representation of all location dynamics for design and manufacturing engineering locations.

Survey Question 17 – How are your company's Product Design data archived?

Table 21

Product Design Data Archive Method

Archive Method	Frequency	Percent
3D Model	54	91.52
2D Electronic CAD Data-Base	35	59.32
2D Manually Drafted Prints	16	27.11
Other	5	8.47

59 survey respondents participated in this question

In Question 17 the respondents were to indicate how their product design data is archived. The survey results for Question 17 are illustrated in Table 21. This question allowed the respondent to choose more than one selection to capture their true archiving methods. Overwhelmingly, 91.52% of the respondents responded that they use the 3D Modeling archive method for storing and retrieving designs. Also of significance, 59.32% of the respondents indicated that the use of 2D electronic CAD Data-Base exists. About a quarter, 27.11%, of the respondents still utilize manually drafted prints for designs, while 8.47% of the respondents indicated that they use other methods in conjunction with 3D modeling. These other methods are most likely custom designed software systems specific to their firm.

Survey Question 18 – What combination of Computer-Aided Tools does your company use? These tools are categorized as:

Computer-Aided Design (CAD)

Computer-Aided Engineering (CAE)

Computer-Aided Manufacturing (CAM)

Table 22

Type of Computer-Aided Tools

Computer-Aided Tools	Frequency	Percent	Cumulative Frequency	Cumulative Percent
CAD	8	13.56	8	13.56
CAD/CAE	9	15.25	17	28.81
CAD/CAM	13	22.03	30	50.85
CAD/CAE/CAM	29	49.15	59	100.00

59 survey respondents participated in this question

For Question 18 the respondents were surveyed regarding the combination of tools utilized in their firm. The survey results for Question 18 are illustrated in Table 22. These were defined and categorized by the combination of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Computer-Aided Manufacturing (CAM). Approximately half, 49.15%, of the respondents indicated that they use all three computer-aided tool types within their firm. CAD/CAM was the next highest usage combination with 22.03% of the responses. The use of only CAD or CAD/CAE represented the smallest response. The responses to this question indicate that not only are firms using CAD as a design and archiving method but also they are utilizing other MCE tools in conjunction with the CAD model.

Survey Question 19 – What type of CAD/CAE/CAM software does your company own?

Table 23

Types of Software Utilized

Software Type	Frequency	Percent
2D Drafting	44	74.57
3D Modeling	57	96.61
Finite Element Analysis (FEA)	37	62.71
Rapid Prototyping (RP)	21	35.59
Computer Aided Process Planning (CAPP)	17	28.81
Computer Numerical Control (CNC)	50	84.74
Product/Process Simulation	23	38.98
Other	0	0

59 survey respondents participated in this question

The respondents in Question 19 were asked what types of software were used within their product and process design phases. The survey results for Question 19 are illustrated in Table 23. The respondent was asked to mark all that applied to their firm. The 3D modeling and 2D drafting were two of the three highest in the groupings representing the CAD-related tools referenced in Question 18. The Computer Numerical Control (CNC) was also one of the highest for respondent response at 84.74%. Computer-Aided Process Planning (CAPP), and

Product/Process Simulation software types represented the CAM related tools as did Finite Element Analysis (FEA) and rapid prototyping (RP) represent the CAE-related tools in Question 18.

Survey Question 20 – How many years of experience does your company have with some form of Computer-Aided Tools?

Table 24

Years of Computer-Aided Tool Experience

Years of Experience	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	1	1.69	1	1.69
1 to 4	0	0	1	1.69
5 to 9	7	11.86	8	13.56
Greater Than 10	51	86.44	59	100.00

59 survey respondents participated in this question

In Question 20 the respondents were to select the category of the number of years regarding their firm's use of computer-aided tool experience. The survey results for Question 20 are illustrated in Table 24. The majority, at 86.4%, of the respondents indicated greater than 10 years of experience with some form of computer-aided tool experience. Only 11.86% indicated they have 5 to 9 years of computer-aided tool experience. There was one respondent who selected no years of experience. These results contradict Question 18, which asked the respondents to select what type of computer-aided tools their firm uses. In Question 18 all respondents indicated some use of computer-aided tools. The researcher assumes that the respondent answered the question concerning his or her own experience with computer-aided tools and not the company's experience. This issue was addressed during other analysis regarding computer-aided tool experience.

Survey Question 21 – Does your company supply training to employees, either internally or externally, to utilize Computer-Aided Tools?

Table 25

Training Supplied for Computer-Aided Tools

Training	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Yes	49	83.05	49	8.05
No	10	16.95	10	100.00

59 survey respondents participated in this question

Question 21 solicited the respondents to concerning their firm's training for the computer-aided tools used. The survey results for Question 21 are illustrated in Table 25. The majority of the respondents indicated that their firm provides some type of training that is needed for the compute-aided tool. Less than a quarter, 16.95%, of the respondents believes that their firm does not provide the adequate training to use the computer-aided tools they have.

Survey Question 22 – How many Design Engineers use Computer-Aided Tools?

Table 26

Design Engineers Utilization of Computer-Aided Tools

Quantity of Design Engineers	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	4	6.78	4	6.78
1 to 19	25	42.37	29	49.15
20 to 99	13	22.03	42	71.19
100 +	17	28.81	59	100.00

59 survey respondents participated in this question

In Question 22 the respondents were asked to quantify the number of design engineers the respondent's firms have that use computer-aided tools. The survey results for Question 22 are illustrated in Table 26. The survey data illustrates that 40.68% of the respondents respond that they have at least 1 design engineer but less than 20 design engineers that utilize computer-aided tools. Another 22.03 % of respondents indicate that they have 20 to 99 design engineers. Furthermore, 28.81% of the respondents indicate that they have over 100 design engineers in their firm's employment. Lastly 8.47% of the respondents responded that they have no distinct design engineering position. Overall, excluding the four respondents who have no design engineer experience, the survey sample represents each of the three populated design engineer categories.

Survey Question 23 – How many Manufacturing / Process Engineers use Computer Aided Tools?

Table 27

Manufacturing / Process Engineers Utilization of Computer-Aided Tools

Quantity of Engineers	Frequency	Percent	Cumulative Frequency	Cumulative Percent
None	4	6.78	4	6.78
1-19 Manufacturing / Process	34	57.63	38	64.41
20-99 Manufacturing / Process	9	15.25	47	79.66
100+ Manufacturing / Process	12	20.34	59	100.00

59 survey respondents participated in this question

The respondents were asked in survey Question 23 to quantify the number of manufacturing / process engineers within the respondent's firm who use computer-aided tools. The survey results for Question 23 are illustrated in Table 27. The survey data illustrates that 57.63% of the respondents respond that they have at least 1 process engineer but less than 20 process engineers that use computer-aided tools. Another 15.25 % of respondents indicate that they have 20 to 99 process engineers. Furthermore, 20.34% of the respondents indicate that they have over 100 process engineers in their firm's employment. Lastly, 6.78% of the respondents responded that they have no distinct process engineering position that utilizes computer-aided tools. Overall, excluding the four respondents who have no process engineer experience, the survey sample represents each of the three populated process engineer categories.

Survey Question 24 – What functions does the individual who creates the 3D computer model perform?

Table 28

Job Functions of 3D Modeler

Job Function	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Drafting/Detailing only	5	8.47	5	8.47
Prod. Design, Drafting/Detailing	23	38.98	28	47.46
Prod. & Process Design, Drafting/Detailing	31	52.54	59	100.00
Do not use Computer Modeling	0	0	59	100.00

59 survey respondents participated in this question

In Question 24 the respondents were solicited to classify the job functions of the 3D modeler. The survey results for Question 24 are illustrated in Table 28. Per the results, 52.54% of the individuals surveyed responded that the job function that the 3D modeler performed included the product and process design along with the drafting and detailing of prints. Also of significance, 38.98% of the respondents indicated that the job function of their 3D modeler was to produce product designs and their corresponding drafting and design prints if required. Thus, 91.53% of the surveyed individuals indicate that their 3D modeler performs the product design and any drafting and detailing as required. In contrast there were 8.47% of the respondents that have drafting and detailing only as the job function.

Survey Question 25 – List your company's perceived or known issue(s) with the utilization of Computer Modeling implementation and sustainability.

Table 29

MCE Categorized Issues

Issues	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Business Systems	45	40.54	45	40.54
Economics	9	8.11	54	48.65
Information Translation	18	16.21	72	65.86
Maintenance	5	4.51	77	6.31
Standards	11	9.91	88	79.28
Time	3	2.71	91	81.98
Training	20	18.01	111	100.00

59 survey respondents participated in this question resulting in 111 issues

In Question 25 the respondents were asked to list their company's perceived or known issue(s) with the utilization of Computer Modeling implementation and sustainability. The list of issues from the respondents is presented in Appendix D of this study. The researcher categorized the list of issues received from the survey into seven categories based on commonality of the results. These categories included:

- Business Systems.
- Economics.

- Information Translation.
- Maintenance.
- Standards.
- Time.
- Training.

Some of the issues were directly related to the categorized subject, such as model translation issues. However, some of the issues related to more than one area, such as converting legacy data into 3D models. This issue could be a result of several of the categories, including the cost of the transfer, the time of converting, and the software challenges. These types of issues were noted as business systems issues. These types of issues have a larger impact on the business.

The categorized survey results for Question 25 are illustrated in Table 29. The business system category had the largest impact concerning the MCE issues. Training had the second highest percentage on the issues list, 18.01%. Even though 80% of the respondents indicated that their firm provided training (Survey Question 21), the training does not seem to be effective due to the large response of training issues. Information translation between the models also has a high percentage of issues, 16.21%. These issues range from incompatible software within the firms IT structure to loss of data during MCE environment communications.

In this second section, each research question was addressed with its corresponding survey data and hypothesis.

Research Question 1: What is the average level of Model-Centric Engineering utilization among manufacturing firms?

The average level of MCE utilization was concluded from Survey Questions 18, 19, 20, and 24 of the survey. Question 18 defined what combination of computer-aided tools firms are currently utilizing. These were categorized by the combination of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Computer-Aided Manufacturing (CAM). Almost 50% of the respondents utilize CAD, CAE, and CAM. Approximately 23% of the respondents support the use of CAD and CAM. There are only a small percentage of respondents using just CAD or CAD with CAE. This indicates that not only are firms using CAD as a design and archiving method but they are also utilizing other MCE tools in conjunction with the CAD model.

The results of Question 19 provided insight on the types of computer-aided software that firms are implementing and maintaining to monitor their product life cycle. The responses illustrated that all types of software are being utilized, but some are more likely to be used than others. CAD software, either 2D or 3D, is the most utilized due to it being the creator and data source of the product design. Manufacturing and design software such CNC and FEA were ranked high per the survey results. These three types of software illustrate the typical software makeup of an MCE environment.

The respondent's data from Question 20 illustrated the current experience level measured in years of implementation of MCE tools. The majority, 86.4%, of the respondents indicated greater than 10 years of experience with some form of computer aided tool experience. Although 11.86% indicated that they have 5 to 9 years of computer-aided tool experience, the majority of the respondents had extensive experience.

Lastly, information captured from Question 24 provided insight on what functions the CAD modeler is performing regarding his or her job. Per the results, 52.54% of the individuals surveyed responded that the job function of their 3D modeler was to perform both product and process design along with the drafting and detailing of prints. Similarly, 38.98% of the respondents indicated that the job function of their 3D modeler produced only product designs and their corresponding drafting and design prints if required. In total, 91.53% of the surveyed individuals indicate that their 3D modeler performs at least the product design and possibly any drafting and detailing required. In contrast there was 8.47% of the respondents that have drafting and detailing only as a job function. This is significant since it validates that firms are moving away from having detailers and drafters and moving towards having joint job functions.

Research Question 2: What types of issues from implementing and utilizing Model Centric Engineering do firms encounter?

The majority of the issues identified related to business systems and not software performance. Issues such as inconsistency between departments, model etiquette, and coordination between the firm’s suppliers plague the MCE success. Even though the software has the capabilities, a firm’s business system may make it difficult to successfully sustain and maintain an issue free MCE environment. A firm’s policies, procedures, and strategic planning do not take into account all of the caveats of fully using MCE. Refer back to results of survey Question 25 regarding MCE issues.

Research Question 3: Is there a relationship between the sizes of manufacturing firms due to the implementation of MCE and the initial time-to-market and agility to accommodate customer-required change?

H_{01}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the size of a manufacturing firm.

H_{A1}: $\Theta \neq 1$. There is a statistically significant relationship between the initial time-to-market and the size of a manufacturing firm.

H_{02}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

H_{A2}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

The response to this question was determined by analyzing the size of the firm defined by both the number of employees and the average amount of company sales to the time-to-market and the ability to accommodate customer-required changes. The following contingency tables for Question 3 were analyzed utilizing Fisher's exact test for statistical significance.

Assumptions for Question 3 include:

- Data was randomly sampled.
- Directional hypothesis.
- Independent observations.
- Dichotomous level of measurement.

Contingency Table 30 was developed using the research survey data from Question 4 regarding company size (defined by the number of employees) and Question 10 relating to time-to-market. Contingency Table 31 was developed using the research survey data from Question 5 pertaining to company sales and Question 10 regarding time-to-market.

Table 30

Employees by Time-to-Market Contingency Table

Employees	0 to 6 Months	6 - 12 Months	1 to 2 Years	Greater Than 2 Years	Total
1 to 499					
Frequency	11	7	11	1	30
Percent	18.64	11.86	18.64	1.69	50.85
Row Percent	36.67	23.33	36.67	3.33	
Column Percents	84.62	70.00	50.00	7.14	
500 to 2499					
Frequency	2	2	4	3	11
Percent	3.39	3.39	6.78	5.08	18.64
Row Percent	18.18	18.18	36.36	27.27	
Column Percents	15.38	20.00	18.18	21.43	
Greater than 2500					
Frequency	0	1	7	10	18
Percent	0.00	1.69	11.86	16.95	30.51
Row Percent	0.00	5.56	38.89	55.56	
Column Percents	0.00	10.00	31.82	71.43	
Total					
Frequency	13	10	22	14	59
Percent	22.03	16.95	37.29	23.73	100.00

Table Probability (P) = 1.279E-08 ρ = 2.519E-04

Table 31

Company Sales by Time-to-Market Contingency Table

Company Sales	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
$0 to $100 Million					
Frequency	11	5	8	0	24
Percent	18.97	8.62	13.79	0.00	50.85
Row Percent	45.83	20.83	33.33	0.00	
Column Percent	84.62	50.00	38.10	0.00	
$100 to $400 Million					
Frequency	1	4	2	3	10
Percent	1.72	6.90	3.45	5.17	17.24
Row Percent	10.00	40.00	20.00	30.00	
Column Percent	7.69	40.00	9.52	21.43	
Greater than $400 Million					
Frequency	1	1	11	11	24
Percent	1.72	1.72	18.97	18.97	41.38
Row Percent	4.17	4.17	45.83	45.83	
Column Percent	7.69	10.00	45.83	78.57	
Totals					
Frequency	13	10	21	14	58
Percent	22.41	17.24	36.21	24.14	100.00

Table Probability (P) = 6.749E-10 ρ = 1.089E-05

Utilizing Fisher's exact test in contingency Table 30, there was a significant relationship between the time-to-market and the number of employees in the firm illustrated by $\rho = .000$ which is below an alpha level of .05. This result was similar for the evaluation of time-to-market and the amount of company sales from the analysis in contingency Table 31. The statistical results of $\rho = .000$, which is below the alpha level set at .05, also concluded that there is a significant relationship between time-to-market and company sales. Based upon the results of both number of employees and the amount of sales compared to time-to-market, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A1}: $\Theta \neq 1$. There is a statistically significant relationship between the initial time-to-market and the size of a manufacturing firm.

The contingency tables illustrated that the smaller firms had a shorter time-to-market, where as the larger firms had a longer time-to-market. This is also true comparing the company sales to time-to-market. Firms who had smaller sales also had a shorter time-to-market. In contrast, firms with large amount of sales had a longer time-to-market. These results seem logical because larger companies tend to build larger products, which require more time and capital.

Contingency Table 32 was developed using the research survey data from Question 4 company size (defined by the number of employees) and Question 11 agility to accommodate customer-required change. Contingency Table 33 was developed using the research survey data from Question 5, company sales, and Question 11 regarding agility to accommodate customer-required change.

Table 32

Company Size by Time for Customer Change Request Contingency Table

Company Size	Less Than 1 Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
1 to 499 Employees					
Frequency	7	6	8	9	30
Percent	11.86	10.17	13.56	15.25	50.85
Row Percent	23.33	20.00	26.67	30.00	
Column Percent	100.00	60.00	50.00	34.62	
500 to 2499 Employees					
Frequency	0	4	4	3	11
Percent	0.00	6.78	6.78	5.08	18.64
Row Percent	0.00	36.36	36.36	27.27	
Column Percent	0.00	40.00	25.00	11.54	
Greater Than 2500 Employees					
Frequency	0	0	4	14	18
Percent	0.00	0.00	6.78	23.73	30.51
Row Percent	0.00	0.00	22.22	77.78	
Column Percent	0.00	0.00	25.00	53.85	
Total					
Frequency	7	10	16	26	59
Percent	11.86	16.95	27.12	44.07	100.00

Table Probability (P) = 1.965E-07 ρ = .0024

Table 33

Company Sales by Time for Customer Change Request Contingency Table

Company Sales	0 to 6 Months	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
$0 to $100 Million					
Frequency	7	5	7	5	24
Percent	12.07	8.62	12.07	8.62	41.38
Row Percent	29.17	20.83	29.17	20.83	
Column Percent	100.00	50.00	43.75	20.00	
$100 to $400 Million					
Frequency	0	4	1	5	10
Percent	0.00	6.90	1.72	8.62	17.24
Row Percent	0.00	40.00	10.00	50.00	
Column Percent	0.00	40.00	6.25	20.00	
Greater Than $400 Million					
Frequency	0.00	1	8	15	24
Percent	0.00	1.72	13.79	25.86	41.38
Row Percent	0.00	4.17	33.33	62.50	
Column Percent	0.00	10.00	50.00	60.00	
Totals					58
Frequency	7	10	16	25	
Percent	12.07	17.24	27.59	43.10	100.00

Table Probability (P) = 6.351E-08 ρ = 7.767E-04

Utilizing Fisher's exact test with contingency Table 32, there is a significant relationship between the agility to accommodate customer-required change and the number of employees in the firm illustrated by $\rho = .002$, which is below the alpha level of .05. Again, this result was similar for the evaluation of agility to accommodate customer-required change and the amount of company sales from the analysis in contingency Table 33. The statistical results of $\rho = .000$, which is below the alpha level of .05, concluded that there is a significant relationship between the agility to accommodate customer-required change and company sales. Based upon the results of both number of employees and the amount of sales compared to the agility to accommodate customer-required change, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A2}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the size of a manufacturing firm.

The contingency tables illustrated that the smaller firms were equally distributed over the time for customer change request categories within the survey question. The larger firms though had a longer reaction time to the customer required change request. These results were similar to the comparison of company sales to time for customer change request. The smaller firm's reaction times were equally distributed over the time categories whereas the larger firms distinctly required a longer time to process change requests.

Research Question 4: Is there a relationship between manufacturing firms with or without discrete job functions of employees utilizing MCE and the initial time-to-market and agility to accommodate customer-required change?

H_{03}: $\Theta = 1$. There is no statistically significant relationship between the initial time-to-market and discrete MCE job functions.

H_{A3}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and discrete MCE job functions.

H_{04}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

H_{A4}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

The response to this question was determined by analyzing the job function of the individual who creates the solid model to time-to-market and the agility to accommodate customer-required changes. The following contingency tables for Question 4 were analyzed utilizing Fisher's exact test for statistical significant. Assumptions for this question include:

- Data was randomly sampled.
- Directional hypothesis.
- Independent observations.
- Dichotomous level of measurement.

Contingency Table 34 was developed using the research survey data from Question 24, normal job function, and Question 10 time-to-market.

Table 34

Job Functions by Time for Customer Change Request Contingency Table

Job Functions	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
Drafting/Detailing Only					
Frequency	2	0	2	1	5
Percent	3.39	0.00	3.39	1.69	8.47
Row Percent	40.00	0.00	40.00	20.00	
Column Percent	15.38	0.00	9.09	7.14	
Product Design & Drafting/Detailing					
Frequency	4	3	9	7	23
Percent	6.78	5.08	15.25	11.86	38.98
Row Percent	17.39	13.04	39.13	30.43	
Column Percent	30.77	30.00	40.91	50.00	
Product & Process Design, Drafting/Detailing					
Frequency	7	7	11	6	31
Percent	11.86	11.86	11.64	10.17	52.54
Row Percent	22.58	22.58	35.48	19.35	
Column Percent	53.85	70.00	50.00	42.86	
Total					
Frequency	13	10	22	14	59
Percent	22.03	16.95	37.29	23.73	100.00

Table Probability (P) = 5.296E-04 ρ = .8336

Utilizing Fisher's exact test with contingency Table 34, there is not enough evidence to sufficiently determine that no significant relationship exists between the time-to-market and job functions illustrated by $\rho = .833$, which is above the alpha level of .05. The result for this hypothesis is failure to reject the null hypothesis.

H_{03}: $\Theta = 1$. There is no statistically significant relationship between the initial time-to-market and discrete MCE job functions.

Contingency Table 35 was developed using the research survey data from Question 24 normal job function and Question 11 agility to accommodate customer-required change.

Table 35

Job Function by Time for Customer Change Request Contingency Table

Job Function	Less Than 1 Month	1 to 2 Months	3 to 6 Months	6+ Months	Total
Drafting/Detailing Only					
Frequency	1	1	0	3	5
Percent	1.69	1.69	0.00	5.08	8.47
Row Percent	20.00	20.00	0.00	60.00	
Column Percent	14.29	10.00	0.00	11.54	
Product Design, Drafting/Detailing					
Frequency	1	4	7	11	23
Percent	1.69	6.78	11.86	18.64	38.98
Row Percent	4.35	17.39	30.43	47.83	
Column Percent	14.29	40.00	43.75	42.31	
Product & Process Design, Drafting/Detailing					
Frequency	5	5	9	12	31
Percent	8.47	8.47	15.25	20.34	52.54
Row Percent	16.13	16.13	29.03	38.71	
Column Percent	71.43	50.00	56.25	46.15	
Total					
Frequency	7	10	16	26	59
Percent	11.86	16.95	27.12	44.07	100.00

Table Probability (P) = 3.915E-04 ρ = .6132

Utilizing Fisher's exact test with contingency Table 35, there is not enough evidence to sufficiently determine that no significant relationship exists between agility to accommodate customer-required changes and job functions. This is illustrated by $\rho = .613$, which is above the alpha level of .05. The result for this hypothesis is also failure to reject the null hypothesis.

H_{04}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and discrete MCE job functions.

Both Hypothesis 3 and 4 lacks the statistical significance needed to reject the null hypothesis and determine a significant variable relationship. No relationship can be statistically derived from these hypotheses.

Research Question 5: Is there a relationship between manufacturing firm's experience levels of MCE and the initial time-to-market and agility to accommodate customer-required change?

H_{05}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

H_{A5}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

H_{06}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

H_{A6}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

The response to this question was determined by analyzing the respondent's firm's experience with MCE in relationship to time-to-market and the agility to accommodate customer-required changes. The following contingency tables for Question 5 were analyzed utilizing Fisher's exact test for statistical significance. Assumptions for Question 5 include:

- Data was randomly sampled.
- Directional hypothesis.
- Independent observations.
- Dichotomous level of measurement.

Contingency Table 36 was developed using the research survey data from Question 20, years of MCE experience, and Question 10, time-to-market. Contingency Table 37 was developed using the research survey data from Question 18, combination of computer aided tools, and Question 10, time-to-market.

Table 36

Experience by Time-to-Market Contingency Table

Experience	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
5 to 9 Years					
Frequency	1	4	2	0	7
Percent	1.72	6.90	3.45	0.00	12.07
Row Percent	14.29	57.14	28.57	0.00	
Column Percent	8.33	40.00	9.09	0.00	
Greater Than 10 Years					
Frequency	11	6	20	14	51
Percent	18.97	10.34	34.48	24.14	87.93
Row Percent	21.57	11.76	39.22	27.45	
Column Percent	91.67	60.00	90.91	100.00	
Totals					
Frequency	12	10	22	14	58
Percent	20.69	17.24	37.93	24.14	100.00

Table Probability (P) = .0019 ρ = .0312

Table 37

Computer-Aided Tools by Time-to-Market Contingency Table

Computer Aided Tools	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
CAD					
Frequency	3	2	3	0	8
Percent	5.08	3.39	5.08	0.00	13.56
Row Percent	37.50	25.00	37.50	0.00	
Column Percent	23.08	20.00	13.64	0.00	
CAD/CAE					
Frequency	2	0	5	2	9
Percent	3.39	0.00	8.47	3.39	15.25
Row Percent	22.22	0.00	55.56	22.22	
Column Percent	15.38	0.00	27.73	14.29	
CAD/CAM					
Frequency	4	4	2	3	13
Percent	6.78	6.78	3.39	5.08	22.03
Row Percent	30.77	30.77	15.38	23.08	
Column Percent	30.77	4.00	9.09	21.43	

Table 37 (continued).

Computer Aided Tools	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
CAD/CAE/CAM					
Frequency	4	4	12	9	29
Percent	6.78	6.78	20.34	15.25	49.15
Row Percent	13.79	13.79	41.38	31.03	
Column Percent	30.77	40.00	54.55	64.29	
Total					
Frequency	13	10	22	14	59
Percent	22.03	16.95	37.29	23.73	100.00

Table Probability (P) = 5.378E-07 $\rho = .2300$

Utilizing Fisher's exact test with contingency Table 36 there is a significant relationship between the time-to-market and the number of years of experience as illustrated by $\rho = .031$, which is below alpha level .05. Based upon the years of experience compared to the time-to-market, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A5}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

In contrast, analyzing contingency Table 37, there is not enough evidence to sufficiently determine that no significant relationship exists between the type of computer-aided tools and time-to-market based upon the statistical results of $\rho = .230$, which is above the alpha level of

.05. The result for the same hypothesis is failure to reject the null hypothesis based on computer-aided type tools.

H_{05}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and a firm's level of MCE experience.

There is significance evidence that there is a relationship between the years of experience with computer-aided tools and time-to-market. The majority of the firms with greater than 10 years of experience resulted in a time-to-market of two years or less, yet but was somewhat equally distributed over the time-to-market categories. However, there is no evidence to support a relationship between the computer-aided tool type and time-to-market. From these results, a relationship between MCE experience and time-to-market can only be referenced to the years of experience with computer aided tools and not by the type.

Contingency Table 38 was developed using the research survey data from Question 20, years of MCE experience, and Question 11, agility to accommodate customer-required change. Contingency Table 39 was developed using the research survey data from Question 18, combination of computer-aided tools and Question 11, agility to accommodate customer-required change.

Table 38

Experience by Time for Customer Change Request Contingency Table

Experience	Less Than 1Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
5 to 9 Years					
Frequency	0	2	3	2	7
Percent	0.00	3.45	5.17	3.45	12.07
Row Percent	0.00	28.57	42.86	28.57	
Column Percent	0.00	20.00	18.75	7.69	
Greater than 10 Years					
Frequency	6	8	13	24	51
Percent	10.34	13.79	22.41	41.38	87.93
Row Percent	11.76	15.69	25.49	47.06	
Column Percent	100.00	80.00	81.25	92.31	
Totals					
Frequency	6	10	16	26	58
Percent	10.34	17.24	27.59	44.38	100.00

Table Probability (P) = .0272 ρ = .4630

Table 39

Computer Aided Tools by Time for Customer Change Request Contingency Table

Computer Aided Tools	Less Than 1 Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
CAD					
Frequency	2	0	2	4	8
Percent	3.39	0.00	3.39	6.78	13.56
Row Percent	25.00	0.00	25.00	50.00	
Column Percent	28.57	00.00	12.50	15.38	
CAD/CAE					
Frequency	1	1	3	4	9
Percent	1.69	1.69	5.08	6.78	15.25
Row Percent	11.11	11.11	33.33	44.44	
Column Percent	14.29	10.00	18.75	15.38	
CAD/CAM					
Frequency	2	5	3	3	13
Percent	3.39	8.47	5.08	5.08	22.03
Row Percent	15.38	38.46	23.08	23.08	
Column Percent	28.57	50.00	18.75	11.54	

Table 39 (continued).

Computer Aided Tools	Less Than 1 Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
CAD/CAE/CAM					
Frequency	2	4	8	15	29
Percent	3.39	6.78	13.56	25.42	49.15
Row Percent	6.90	13.79	27.59	51.72	
Column Percent	28.57	40.00	50.00	57.69	
Total					
Frequency	7	10	16	26	59
Percent	11.86	16.95	27.12	44.07	100.00

Table Probability (P) = 2.966E-06 ρ = .4448

Utilizing Fisher's exact test with contingency Table 38, there is not enough evidence to sufficiently determine that no significant relationship exists between agility to accommodate customer-required changes and years of experience with computer aided tools, as illustrated by a ρ = .463, which is above the alpha level of .05. Similarly, utilizing Fisher's exact test with contingency Table 39, there is also not enough evidence to sufficiently determine that no significant relationship exists between agility to accommodate customer-required change and the type of computer-aided tools, as illustrated by a ρ = .445, which is above the alpha level of .05. The result for this hypothesis is also failure to reject the null hypothesis.

H_{06}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and a firm's level of MCE experience.

Both Hypothesis 5 and 6 lack the statistical significance to reject the null hypothesis to determine significant variable relationship. There was some relationship between the years of experience compared to time-to-market but no clear relationship was present in the contingency table. The results were equally distributed over the time-to-market categories. These results concluded that no evidence existed to support a relationship of time-to-market and agility to accommodate customer change dependent on the MCE experience level.

Research Question 6: Is there a relationship between manufacturing firm's engineering groups that are or are not co-located and the initial time-to-market and agility to accommodate customer-required change?

H_{07}: $\Theta = 1$. There is no statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

H_{A7}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

H_{08}: $\Theta = 1$. There is no statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

H_{A8}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

The response to this question was determined by analyzing location of the engineering departments to time-to-market and the agility to accommodate customer-required change. The following contingency tables for Question 6 were analyzed utilizing Fisher's exact test for statistical significant. Assumptions for this question include:

- Data was randomly sampled.
- Directional hypothesis.
- Independent observations.
- Dichotomous level of measurement.

Contingency Table 40 was developed using the research survey data from Question 16, engineering location and Question 10, time-to-market.

Table 40

Engineer Location by Time-to-Market Contingency Table

Engineer Location	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
Co-located, same building					
Frequency	10	8	6	3	27
Percent	16.95	13.56	10.17	5.08	45.76
Row Percent	37.04	29.63	22.22	11.11	
Column Percent	76.92	80.00	27.27	21.43	
Same facility, different building					
Frequency	0	2	3	7	12
Percent	0.00	3.39	5.08	11.86	20.34
Row Percent	0.00	16.67	25.00	58.33	
Column Percent	0.00	20.00	13.64	50.00	
Same company, different facility					
Frequency	1	0	12	2	15
Percent	3.39	0.00	20.34	3.39	25.42
Row Percent	18.18	0.00	80.00	13.33	
Column Percent	15.38	0.00	54.55	14.29	

Table 40 (continued).

Engineer Location	0 to 6 Months	6 to 12 Months	1 to 2 Years	Greater Than 2 Years	Total
Different company, different facility					
Frequency	2	0	1	2	5
Percent	3.39	0.00	1.69	3.39	8.47
Row Percent	40.00	0.00	20.00	40.00	
Column Percent	15.38	0.00	4.55	12.29	
Total					
Frequency	13	10	22	14	59
Percent	22.03	16.95	37.29	23.73	100.00

Table Probability (P) = 8.921E-11 ρ = .0006

Utilizing Fisher's Exact Test with contingency Table 40, there is a significant relationship between the time-to-market and engineering location, as illustrated by ρ = .001, which is below an alpha level of .05. Based upon the results of engineering location compared to time-to-market, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A7}: $\Theta \neq 1$. There is a statistically significant relationship between initial time-to-market and the collocation of a firm's engineering groups.

Contingency Table 41 was developed using the research survey data from Question 16 engineering location and Question 11 agility to accommodate customer-required change.

Table 41

Engineer Location by Customer Change Request Contingency Table

Engineer Location	Less Than 1 Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
Co-located, same building					
Frequency	6	9	5	7	27
Percent	10.17	15.25	8.47	11.86	45.76
Row Percent	22.22	33.33	18.52	25.93	
Column Percent	85.71	90.00	31.25	26.92	
Same facility, different building					
Frequency	0	0	4	8	12
Percent	0.00	0.00	6.78	13.56	20.34
Row Percent	0.00	0.00	33.33	66.67	
Column Percent	0.00	0.00	25.00	30.77	
Same company, different facility					
Frequency	1	0	4	10	15
Percent	1.69	0.00	6.78	16.95	25.42
Row Percent	6.67	0.00	26.67	66.67	
Column Percent	14.29	0.00	25.00	38.46	

Table 41 (continued).

Engineer Location	Less Than 1 Month	1 to 2 Months	3 to 6 Months	Greater Than 6 Months	Total
Different company, different facility					
Frequency	0	1	3	1	5
Percent	0.00	1.69	5.08	1.69	8.47
Row Percent	0.00	20.00	60.00	20.00	
Column Percent	0.00	10.00	18.75	3.85	
Total					
Frequency	7	10	16	26	59
Percent	11.86	16.95	27.12	44.07	100.00

Table Probability (P) = 1.140E-06 $\rho = .0048$

Utilizing Fisher's Exact Test with contingency Table 41, there is not enough evidence to sufficiently determine that no significant relationship exists between agility to accommodate customer-required change and job functions, as illustrated by $\rho = .005$ which is above the alpha level of .05. The result for this hypothesis is also failure to reject the null hypothesis.

H_{A8}: $\Theta \neq 1$. There is a statistically significant relationship between agility to accommodate customer-required changes and the collocation of a firm's engineering groups.

The contingency tables illustrated that engineering groups which are collocated in the same building have a shorter time-to-market than engineering groups located by significant distance. In comparison engineering groups that are collocated in the same building have varying reaction times to accommodate customer changes but the engineering groups that are not collocated still have longer reaction times to customer change requests.

Research Question 7: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level compared to initial time-to-market?

H_{09}: $\beta_j = 0$. There is no statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

H_{A9}: $\beta_j \neq 0$. There is a statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Based upon the statistical analysis in Chapter 4, there were two independent variables that were determined significant illustrated by a $\rho = .000$. These independent variables were product complexity level and engineering location. Based upon the results of engineering location of product complexity level, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A9}: $\beta_j \neq 0$. There is a statistically significant relationship between initial time-to-market and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

The logistic regression equation is as follows:

$\log(\Theta(x)) = -1.397 - 2.078*X1a - 0.3584*X1b + 2.3927*X2a + 0.2951*X2b - 2.8849*X2c$

X1 corresponds to Question 9 regarding the complexity level of the product. X2 corresponds to question 16 describing the physical location of the engineering groups. X1a is the effect of changing to complete vehicle assembly and integration from single component/piece parts. X1b is the effect of changing to major and minor subassembly builds from single component. X2a is the effect of changing from co-located in the same building located in the same facility but a different building. X2b is the effect of changing to a different company (sub-contractor) and a different facility from a same facility but a different building. X2c is the effect of changing to the same company but different facility from the same facility but a different building. The y-intercept is equaled to -1.397 for this equation.

Research Question 8: What is the relationship of MCE practices, manufacturing firm size, discrete job functions, production volume, product complexity, company sales, engineering location, software implementation, and MCE experience level compared to agility to accommodate customer-required change?

H_{010}: $\beta_j = 0$. There is no statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

H_{A10}: $\beta_j \neq 0$. There is a statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Based upon the statistical analysis in Chapter 4, there was one independent variable that was significantly illustrated by $\rho = .002$, which is below the .05 level. This independent variable was firm size. Based upon the results of the firm's size by population and its relationship to agility to accommodate customer-required change, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A10}: $\beta_j \neq 0$. There is a statistically significant relationship between agility to accommodate customer-required change and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

The logistic regression equation is as follows:

$$\log(\Theta\ (x)) = 0.1918 + 0.6555\ X1a + 0.7890\ X1b$$

X1 corresponds to question 4 regarding the respondent's company size determined by the number of employees. X1a is the effect of changing from a category of greater than 2500 employees to a category of 1 to 499 employees.

X1b is the effect of changing from a category of greater than 2500 employees to a category of 500 to 2499 employees. The y-intercept is equaled to 0.1918 for this equation.

Research Question 9: What is the relationship of MCE practices, manufacturing firm size; discrete job functions, production volume, product complexity, engineering location, software implementation, and MCE experience level compared to company sales?

H_{011}: $\beta_j = 0$. There is no statistically significant relationship between company sales trends and the collective factors of MCE practices, manufacturing firm size, discrete MCE job functions, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

H_{A11}: $\beta_j \neq 0$. There is a statistically significant relationship between company sales trends and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

Based upon the statistical analysis in chapter 4, there was one independent variable that was significant illustrated by $\rho = .002$, which is below the .05 level. This independent variable was the firm's product complexity. Based upon the results of the firm's product complexity and its relationship to company sales, the null hypothesis is rejected and the alternative hypothesis is retained.

H_{A11}: $\beta_j \neq 0$. There is a statistically significant relationship between company sales trends and the collective factors of MCE practices, manufacturing firm size, discrete MCE job function, production volume, product complexity, sales, engineer location, software implementation, and MCE experience.

The logistic regression equation is as follows:

$\log(\Theta(x)) = 0.2759 - 1.7422\,X1a + 0.2837\,X1b$

X1 corresponds to question 9 regarding the complexity level of the respondent's product. X1a is the effect of changing to complete vehicle assembly and integration from single component/piece parts. X1b is the effect of changing to major and minor subassembly builds from single component piece parts. The y-intercept is equal to 0.2759 for this equation.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Globalization and technology transfer is creating a more competitive market for manufacturing firms. Although still very important, current competitive measures of cost, quality and schedule are no longer the only items firms must monitor to be successful. Firms must now also focus on time-to-market and the ability to accommodate customer-required changes in order to react to their customer's needs while still obtaining a low cost, high quality, and on-schedule product. To shorten time-to-market, firms implement MCE technology in the hopes of lessoning the response time to customer requests for a new product or a change to an existing product.

Manufacturing firms commonly assume that using MCE decreases time-to-market by reducing design time and reducing productivity issues. They also assume that utilizing MCE provides greater agility for change, thus facilitating increased customer satisfaction. However, there is minimal scholarly data published to substantiate these assumptions. Software companies that create and market model-centric technology provide the most supporting data on this subject, but this information has inherent bias and may fail to recognize potential issues that inhibit the desired outcome of MCE. Having the functionality of engineering software does not necessarily mean success—neither does the incorporation of MCE software into current business systems. Conversely, it may be possible that software companies are not maximizing on the extent to which the software is providing greater agility and increased satisfaction because they have not fully explored this correlation themselves.

The purpose of this study was to investigate the relationship between the use of model-centric engineering and a firm's competitiveness as defined by time-to-market and agility to accommodate customer-required changes. The study focused on two areas. The first area of focus pertained to defining the current model-centric environment in manufacturing by factors such as level of usage, years of experience, discrete MCE job functions, implementation, and usage. The second area of focus concentrated on the relationship between the utilization of MCE and the competitiveness of a company. This was defined by the relationship between time-to-market, agility to accommodate customer-required change, number of employees, company sales, job functions, computer aided tools, years of experience with MCE, engineering locations, production volume, and software implementation. These two areas of focus for the study were addressed by the 9 research questions identified within the study.

The average usage level of MCE among manufacturing firms was determined by four variables. These included the combination of computer aided tools utilized, the type of CAD/CAE/CAM software implemented, years of experience regarding MCE use, and the job function of the 3D modeler. From the data provided by the survey respondents, almost half of the respondents indicated use of all three computer aided tools. This result was confirmed by the large percentage of software respondents indicated their firms used to support CAD/CAE/CAM processes. Just fewer than 97% of the respondents indicated 3D modeling was used to document their product design which creates the central hub and data repository for MCE. Almost 87% of the respondents had greater than 10 years of experience with some form of computer-aided tools, and another 12% of the respondents had between 5 and 10 years of experience with computer aided tools. Thus combined, a significant portion of the respondents (99%) had 5 or more years of experience with computer-aided tools. Approximately 52% of the respondents indicated that the 3D modeler provided more than just a drafting and detailing job function. These additional tasks included engineering tasks related to product and process design. Almost as significant is the additional 40% of respondents that selected that their 3D model job functions as a combination of design engineering, drafting and detailing. It was concluded from this study, that the respondents have an extensive amount of MCE experience based upon years of experience, types and variations of computer aided tools, and the types of software they are utilizing.

MCE implementation and utilization issues were also identified in this study. Each was classified into related groups to describe the major issues identified with MCE. Issues related to business systems made up 40% of the issues that presented the most problems per the respondents. These issues included items that affected policies, procedures, strategic initiatives, and other business type systems. These issues may directly or indirectly relate to other issues referenced in this section such as funding, data translation, and modeling standards.

Economics of MCE presented itself as another issue for firms representing 8% of the total responses. Firms are forced to make a large capital expenditure to procure and maintain software for MCE. On top of this cost, training is required for employees who will be using this software, creating additional cost burdened by the firm. Having a high implementation cost may shy firms away from procuring all the needed software for MCE to function as intended by supporting the business practices. This causes gaps within the business system of the firm, in which alternative methods or workarounds are created to bridge the gap, resulting in a disjointed environment where additional effort is needed to fully realize MCE's benefits.

The information translation or data transfer is a major issue for firms, representing approximately 16% of the recorded issues. This includes issues from data transferring from software to software, data transferred from software to machine equipment, or data transferred from paper to a 3D modeling tool. This issue results in additional time and cost, as well as possible data loss or inadvertent data changes.

The lack of modeling standards, maintenance, and training creates other potential issues that can plague the MCE environment. MCE is a complex methodology that requires discipline to be successful. The 3D model must have an environment where data is strictly controlled and maintained by individuals who have the appropriate knowledge and skills. It is evident by the identified respondent issues that proper training and discipline in the MCE environment is necessary to be successful.

Through hypothesis testing it was determined that there was a relationship between the size of manufacturing firms and both initial time-to-market and agility to accommodate customer-required change. The size of the firm was determined by the number of employees and by the estimated amount of annual sales.

The survey results illustrated that smaller firms had a shorter time-to-market whereas larger firms had a longer time-to-market. This is also true comparing the company sales to time-to-market. Firms with smaller sales also had a shorter time-to-market. In contrast, firms with large sales had a longer time-to-market. The results of the smaller firms were equally distributed over the categories within the survey question for time to accommodate a customer change request. Conversely, larger firms had a longer reaction time to customer required change requests. These results were similar to the comparison of company sales to time for customer change request. The smaller firm’s reaction times were equally distributed over the time categories whereas the larger firms distinctly required a longer time to process the change request. From the results of the study it was concluded that the larger the firm as defined by employment size and annual sales the longer the time-to-market and time to accommodate customer required change.

Through hypothesis testing, it was determined that there was a lack of statistical evidence to determine a significant variable relationship between manufacturing firms specific discrete employee job functions utilizing MCE and both initial time-to-market and agility to accommodate customer-required change. Thus the null hypothesis was not rejected. Even though there was no significant relationship to MCE pertaining to job functions, it was noted that the job functions are trending away from the traditional design methodology of specific function such as drafter, design engineer, and process engineer. This trend illustrates a high percentage of respondents' firms are combining their positions to create a cross-function job function.

Through hypothesis testing it was determined that there is also a lack of statistical evidence to determine if a significant relationship exists between manufacturing firms experience levels and both initial time-to-market and agility to accommodate customer-required change. Thus, the null hypothesis was not rejected. Although there appeared to be a relationship between the years of experience compared to time-to-market, no clear relationship was present in the contingency table. This lack of statistical evidence does not mean that there was no relationship, but rather that the data gathered from this study did not support a conclusion. This may be due to the small sample size of respondents. The results from the previous questions identified this group of respondents as highly experienced within the MCE environment. This is based on their use of computer-aided tools. Even though their experience level is high it may be based on software knowledge and not based on the relationship to their business systems in supporting MCE.

Through hypothesis testing, it was determined that there is a relationship between the physical location of the engineering groups and both the initial time-to-market and agility to accommodate customer-required change. The contingency tables illustrated that engineering groups which are co-located in the same building have a shorter time-to-market than engineering groups separated by significant distance. In comparison, engineering groups that are collocated in the same building have varying reaction times to accommodate customer changes, but the engineering groups that are not collocated consistently have a longer reaction time to customer change requests. This illustrates a possible communication crutch that may add significant time to the product design life cycle. Even though MCE should enhance communication through data sharing, per the results having the ability for face to face communication still presents advantages over communications through electronic data sharing.

There was some relationship between the independent variables of manufacturing firm size, discrete job functions, production volume, engineering location and the dependent variables of time-to-market, agility to accommodate customer required changes, and company sales. Logistic regression equations were developed by identifying the variables that were considered significant in the relationships. In regards to time-to-market both, product complexity and location of the engineering staff were deemed significant to model a relationship. Each of the other variables analyzed were not significant to the overall relationship. The regression equation to model this relationship is concluded as:

$$\log(\Theta(x)) = -1.397 - 2.078*X1a - 0.3584*X1b + 2.3927*X2a + 0.2951*X2b - 2.8849*X2c$$

In regards to agility to accommodate customer required-changes, the only significant variable for the equation was the firm size. All other variables analyzed were not significant to the overall relationship. The regression equation to model this relationship is concluded as:

$$\log(\Theta(x)) = 0.1918 + 0.6555\ X1a + 0.7890\ X1b$$

Product complexity level was found to be the only variable in this relationship significant enough to predict the relationship of company sales. Again all other variables were not deemed to be of significance. The regression equation to model this relationship is concluded as: $\log(\Theta(x)) = 0.2759 - 1.7422\ X1a + 0.2837\ X1b$

Suggestions for Further Research

The results of this study have assisted in validating and rejecting key assumptions regarding MCE and its relationship industry competiveness. Firms can use this study as a qualitative resource when planning their engineering strategy and developing their business system to enhance manufacturing competitiveness. Topics regarding MCE and its relationship to competitiveness for further research may include:

- Identify key business system drivers that affect MCE utilization.
- Investigate and quantify cost and time impact of MCE business system issues.
- Explore a relationship between MCE and Lean Manufacturing.
- Perform gap analysis on the communication path of engineers utilizing MCE.
- Determine if the findings of this study are similar to other NAICS groups.

Studies on MCE and its relationship to competiveness are relatively untouched. Further studies are needed to analyze the methodology of MCE within a business system and the technology that supports it.

The sample size of 59 respondents fell short of the required 267 respondents to satisfy a margin of error assumption of 5% and a confidence level of 95% for the study. With only 59 respondents for this study's sample the margin of error assumption changed from 5% to 12.74 % while still keeping the confidence level at 95%. Because the number of respondents did not meet the required sample size for the study's parameters, it cannot be concluded that the findings of this research to truly represent the population of the NAICS Transportation Equipment Manufacturing Sector code 336 identified in Chapter 3. The results of this study can only be related to the 59 respondents surveyed. An additional study would need to be conducted to gather enough data to produce a statistically sound conclusion to represent the entire NAICS Transportation Equipment Manufacturing Sector code 336.

The low response rate may have been the result of a short survey timeframe, low amount of interest in the subject, or lack of incentive to participate. Future survey work on this subject may consider incentives for survey participation and presenting the survey to the participants in a more user friendly / comprehensive method. Also with the large majority of engineers participating in this study and most of the variables related to business systems, engineers may not have been comfortable answering questions related to perceived management decisions and functional responsibilities of business systems. These types of questions may need to be targeted to management type positions instead of technical positions.

Conclusion

From the results of this study it was concluded that some variables of MCE do affect a firm's competitiveness defined by the initial time-to-market and the firm's agility to accommodate customer-required changes. The effects from MCE were not based upon the software that supports this method but more from MCE's relationship with the firm's business systems. Items such as collocation of engineers, training of employees, consistency of implementation and usage of MCE tools were found to have a greater impact on time-to-market and agility to accommodate customer-required change. MCE methodology is more than having capable computer aided tools to perform the design and develop processes. MCE requires a strong foundation of policies, procedures, and protocol to allow the computer aided software to function as it is intended and is not hampered by a restrictive or unorganized business system.

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APPENDIX A: SURVEY EMAIL

Subject Line: Model Centric Engineering Dissertation Research Survey

Dear SME Member,

I am a doctoral student at Indiana State University and currently performing my dissertation research. I am requesting your participation to complete an industry survey to gather data for hypothesis testing.

The purpose of my study is to determine if Model Centric Engineering affects a firm's competitiveness defined by time-to-market and the agility to accommodate customer change. Model Centric Engineering for this study is defined by the methodology of utilizing a three-dimensional computer generated model as the center of the design and manufacturing phase of a product life cycle. This three-dimensional model serves as the single source to hold all of the characteristic information digitally of the product from design through process. The use of computer aided design (CAD), computer aided engineering (CAE), and computer aided manufacturing software are typically utilized for engineering analysis and process devolvement to simulate and expedite the product design cycle. The study will focus on two areas. The first will be defining the current Model Centric Environment in manufacturing by factors such as level of usage, years of experience, and discrete job functions of employees utilizing Model Centric Engineering, and implementation and usage issues. The second area will concentrate on the relationship between the utilization of Model Centric Engineering and the competitiveness of a company. This will involve comparing a firm's level of Model Centric Engineering usage to the firm's time-to-market and agility to accommodate customer change. Results from this study will provide a current qualitative representation of Model Centric Engineering's effects on a firm's success in their industry.

The internet survey should take approximately 10 minutes. The survey can only be completed one time by each respondent. The participant will not receive any future emails or other types of communication about their past participation of this study. Each participant should delete the email received through the Society of Manufacturing Engineering concerning this study.

If you agree to participate in this study and would like to continue to the survey please click on the web address below. If you do not agree with the information presented and would not like to participate, please disregard this email.

https://www.surveymonkey.com/s/Model_Centric_Engineering

Thank you for your time and support of my research.

Craig Schroeder,
Doctoral Candidate
Indiana State University
SME Student Member
Phone: 419-296-9258
Cschroeder2@indstate.edu

APPENDIX B: SURVEY COVER LETTER

THE EFFECTS OF MODEL CENTRIC ENGINEERING ON A COMPANY'S TIME-TO-MARKET AND AGILITY TO ACCOMMODATE CUSTOMER CHANGE

PURPOSE OF THE RESEARCH STUDY:

The purpose of this study is to review Model Centric Engineering and the affect on time-to-market and the agility to accommodate customer change. Model Centric Engineering for this study is defined by the methodology of utilizing a three-dimensional computer generated model as the center of the design and manufacturing phase of a product life cycle. This three-dimensional model serves as the single source to hold all of the characteristic information digitally of the product from design through process. The use of computer aided design (CAD), computer aided engineering (CAE), and computer aided manufacturing software are typically utilized for engineering analysis and process devolvement to simulate and expedite the product design cycle.

RESPONDENTS'S RISK, BENEFITS & RIGHTS:

Participation in this research survey is completely voluntary and confidential. No question within the survey asks for any specific identifiable information such as your name, email address, and company name. Responding to this online survey indicates consent to participate in the research study. You may end the survey at any time by closing the web browser.

This survey is of minimal risk. Because there is no contact information or computer tracing information being obtained and forwarded to the principle investigator from the survey respondent, no letter of consent form is required. This survey is distributed through the Society of Manufacturing Engineering so no contact information is shared with the researcher. The benefit to the participants of this study is the knowledge gained from the research on Model Centric Engineering and its relationship to time-to-market and agility to accommodate customer change. No monetary or social benefit is provided for participants in this study.

The internet survey should take approximately 10 minutes. The survey can only be completed one time by each respondent. The participant will not receive any future emails or other types of communication about their past participation of this study. Each participant should delete the email received through the Society of Manufacturing Engineering concerning this study.

The Institutional Review Board (IRB) at Indiana State University has determined this study to be exempt from IRB oversight. If you have any concerns about your rights as a participant in this study you may contact the Human Research Protection Office at 200 North 7th street, Terre Haute, Indiana 47809 [irb@indstate.edu or by telephone (812) 237-8217].

The principal investigator for this study is Craig A. Schroeder. If you have any questions or concerns about completing the survey or about being in this study, you may contact me at 376 Lakeshore Drive, Ottawa, Ohio 45875 [cschroeder2@indstate.edu or by telephone (419) 296-9258]. I thank you for your time and effort in participating in my survey.

If you agree to participate in this study and would like to continue to the survey please click the “Continue Button” below. If you do not agree with the information presented and would not like to participate, please close your browser to exit the survey.

Sincerely,

Craig Schroeder,
Doctoral Candidate
Indiana State University
SME Student Member
Phone: 419-296-9258
Cschroeder2@indstate.edu

[Ref: Indiana State University IRB# 10-155]

APPENDIX C: SURVEY QUESTIONS

1) What is your profession?

- ❑ Engineer
- ❑ Consultant
- ❑ Production Foreman
- ❑ Operations Management
- ❑ Company Executive
- ❑ Other__________

2) What is your job responsibility?

- ❑ Product Design
- ❑ Process Design
- ❑ Quality Assurance
- ❑ Management
- ❑ Production
- ❑ Other__________

3) What is your highest level of College Education?

- ❑ None
- ❑ Certificate
- ❑ Associates
- ❑ Bachelors
- ❑ Masters
- ❑ Doctorate

4) What is your company size?

- ❑ 1 to 499 employees
- ❑ 500 to 2,499 employees
- ❑ 2,500 plus employees

5) What are your company's estimated average total sales?
   - ❑ 0 to 100 million dollars
   - ❑ 100 to 400 million dollars
   - ❑ Greater than 400 million dollars
   - ❑ Unknown

6) What North American Industry Classification System (NAICS) category does your company belong to?
   - ❑ Motorcycle
   - ❑ Automotive / Truck
   - ❑ Aerospace / Missile
   - ❑ Locomotive
   - ❑ Ship / Boat
   - ❑ Military Armor Vehicle
   - ❑ Other__________

7) What is your company's typical production volume for your primary product?
   - ❑ Individual / Custom Build
   - ❑ 1 to 10 product a year
   - ❑ 1 to 10 product a month
   - ❑ 1 to 10 product a week
   - ❑ 1 to 10 product a day
   - ❑ Greater than product 10 a day

8) What is the throughput time of your product through production?
   - ❑ Less than 1 month
   - ❑ 1 to 2 months
   - ❑ 3 to 6 months
   - ❑ Greater than 6 months

9) Describe the level of complexity of your primary product by the following?
   - ❑ Complete Vehicle Assembly and Integration
   - ❑ Major and Minor Sub-Assembly Build
   - ❑ Single Component / Piece Parts

10) What is your average time from the beginning of product concept stage to market delivery?
   - ❑ 0 to 6 months
   - ❑ 6 months to 1 year
   - ❑ 1 to 2 years
   - ❑ 2 years of more

11) What is the average time from initial customer change request to production incorporation?
    - ❑ Less than 1 month
    - ❑ 1 to 2 months
    - ❑ 3 to 6 months
    - ❑ Greater than 6 months

12) How many design changes on average occur during the concept stage to market delivery?
    - ❑ Less than 15
    - ❑ 15 to 25
    - ❑ 25 to 50
    - ❑ Greater than 50

13) How many problem reports or corrective actions on average occur during the concept stage to market delivery?
    - ❑ Less than 15
    - ❑ 15 to 25
    - ❑ 25 to 50
    - ❑ Greater than 50

14) How many Design Engineers within your company?
    - ❑ None
    - ❑ 1 to 19 Design Engineers
    - ❑ 20 to 99 Design Engineers
    - ❑ 100 plus Design Engineers

15) How many Manufacturing / Process Engineers within your company?
    - ❑ None
    - ❑ 1 to 19 Manufacturing / Process Engineers
    - ❑ 20 to 99 Manufacturing / Process Engineers
    - ❑ 100 plus Manufacturing / Process Engineers

16) Describe the physical locations of your design and manufacturing engineering departments?
    - ❑ Co-located in the same Building
    - ❑ Same Facility but different Building
    - ❑ Same Company different Facility
    - ❑ Different Company (Sub-Contractor) different Facility

17) How are your company's Product Design data archived
(Check all that apply)

- ❑ 3D Model
- ❑ 2D Electronic CAD Data Base
- ❑ 2D Manual Drafted Prints
- ❑ Other______________

18) What combination of Computer Aided Tools does you company use?
"Computer Aided Design (CAD)"
"Computer Aided Engineering (CAE)"
"Computer Aided Manufacturing (CAM)"

- ❑ CAD
- ❑ CAD / CAE
- ❑ CAD / CAM
- ❑ CAD / CAE / CAM
- ❑ None

19) What type of CAD/CAE/CAM software does your company own?
(Check all that apply)

- ❑ 2D Drafting
- ❑ 3D Modeling
- ❑ Finite Element Analysis (FEA)
- ❑ Rapid Proto-Typing (RP)
- ❑ Computer Aided Process Planning (CAPP)
- ❑ Computer Numerical Control Programming (CNC)
- ❑ Product / Process Simulation
- ❑ Other_______________

20) How many years of experience does your company have with some form of Computer Aided Tools?

- ❑ None
- ❑ 1 to 4 years
- ❑ 5 to 9 years
- ❑ 10 or more years

21) Does your company supply training to employees either internally or externally to utilize Computer Aided Tools?

- ❑ Yes
- ❑ No

22) How many Design Engineers use Computer Aided Tools?
- ❑ None
- ❑ 1 to 19 Design Engineers
- ❑ 20 to 99 Design Engineers
- ❑ 100 plus Design Engineers

23) How many Manufacturing / Process Engineers use Computer Aided Tools?
- ❑ None
- ❑ 1 to 19 Manufacturing / Process Engineers
- ❑ 20 to 99 Manufacturing / Process Engineers
- ❑ 100 plus Manufacturing / Process Engineers

24) What functions does the individual who creates the 3D Computer model perform?
- ❑ Drafting / Detailing only
- ❑ Product Design and Drafting / Detailing
- ❑ Product Design, Drafting / Detailing, and Process Design
- ❑ Do not use Solid Modeling

25) List the perceived or known issues with the utilization of some level of Computer Modeling implementation and sustainability.

Type Answers in box

1.
2.
3.
4.
5.

APPENDIX D: MCE ISSUES

Business system

- "Difficulty and expense of coordinating multiple systems to run the business. Engineering, procurement, materials, quality, and manufacturing."
- PRO ENGINEER VS CATIA
- Configuration management of tools across supplier base
- Different systems in different departments
- Producibility
- Taking into consideration the manufacturing tolerances when building a 3Dmodel to nominal
- Relating the finished product back to the 3D model and plotting capability analysis on each feature.
- Different Cad Platforms Used
- Use of multiple programs/communication
- Our biggest problem is going from a 3D model to subassemblies that are easy to document and manufacture.
- Products are not designed for manufacturability
- Getting it to work on all of our CNC's (because of different controls and codes)
- Maintaining compatibility with customer
- New revision roll out
- Managing product change
- Oversight of supplier preparation and use of tools
- Collaboration
- "Tracking updates between process engineering, programming, Tool design & manufacturing"
- Too much reliance on out-dated paper methods
- Prototypes necessary
- Old / legacy data
- 3D models aren't organized
- Control of version levels within product groups
- Management understanding
- Legacy systems
- Process Changes
- Lack of focus on using CM tools i.e. continue using traditional methods
- Functional Integration
- Managing various customer modeling revisions

- Different CAD software packages
- Customer requirements
- Concurrent Engineering
- Heavily reliant on drawings
- Full Utilization of software
- Systems integration with structure
- Selecting software
- File management problem
- Revision documentation. Library maintenance.
- Global equalization
- Data Management
- "Revision control, design is never truly frozen"
- Converting old drawings to be model based.
- Updating current process to new customer models
- Transforming hand dwg to CAD
- Not all vendors have software

Economics

- Cost
- "Software updating from year to year, cost"
- Cost
- cost
- Cost
- Costly to continue upgrades for little software improvement
- Software and software support is expensive annual cost
- License fees are expensive
- Cost of supercomputers to handle large-complex modeling
- Model not acceptable for machining

Information Translation

- File transfer
- Can't convert to different software formats
- "Simulation of production processes is very inaccurate, and usually inconclusive."
- Data transfer between CAD/CAE/CAM
- Extracting CAE models from CAD models
- Results of comparable CAD/CAE/CAM systems & time differences.
- Tying the BOM to different productions software
- Translation issues between Japan and USA versions of same software
- It's hard to relay 3D mbd to shop floor
- Model vs. print issues
- Flat pattern translation
- Loss of Detail during CAD translation
- Internal networking

- IGES not always good to import Solid models or surfaces between software packages
- Different customer requirements formats
- Working between different 3D software packages
- Integration with older versions of 2D software

Maintenance

- Getting the bugs worked out of a new release of software
- Maintenance
- "Software updating from year to year, compatibility"
- Software issues
- Updates

Standards

- Process control as applied to models
- Model accuracy
- Lack of Standards
- Standards
- Adherence to design conventions/standards
- Model accuracy
- Effective parametric modeling
- Drawing and models may not agree.
- Tolerance as applied to models
- Model revision control
- Incomplete solids/ models passed to Mfg

Time

- Time consuming
- Time constraints
- Accessing models take long time

Training

- Lack of knowledge in CM tools
- "Training, maintaining a standard practice for all users"
- Training
- Finding qualified personnel
- Not enough training
- Training
- Training
- Training
- Training
- Training
- Training
- Knowledge and skill needs

- Lack of training
- Having the right people in place and trained when the software is needed
- "Old guys"" not understanding data"
- Learning curve for accurately simulate processes
- Training
- Training
- Support issues
- Use of System properly