A Dissertation

entitled

The Impact of Computer-Aided Design (CAD) Systems on Firm Performance

by

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Submitted as partial fulfillment of the requirements for

the Doctor of Philosophy degree in

Manufacturing Management

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Graduate School

The University of Toledo

August 2002

UMI Number: 3058915

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An Abstract of

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Many firms make substantial investment in advanced manufacturing technology (AMT) and information technology (IT) in anticipation of benefits. The advantages realized from these investments have been difficult to assess. This research presents a comprehensive organizational level research model to study the impact of computer-aided design (CAD) on a firm's manufacturing effectiveness, product development process performance, and overall performance.

This study discusses and examines the antecedent relationships between five constructs of interest: Product Development Practices - *Concurrent Engineering*, *Supplier Involvement*, *Customer Involvement*, *Heavyweight Product Development Managers*, and *Platform Products*; multidimensional CAD USAGE – *Engineering Design Usage*, *Cross Functional Usage*, *Integrate with Customers Usage*, and *Integrate with Suppliers Usage*; Manufacturing Effectiveness;

Product Development Process Performance - *Team Process Outcome* and *Team Efficiency*; and Overall Firm Performance - *Value to Customer*.

Analyses are performed using LISREL® for Windows version 8.12a based on 175 usable responses collected via a mailed survey to 2668 firms from five industries (two digit SICs = 30, 34, 35, 37, and 38). The measurement scales for each construct (Product Development Practices, CAD USAGE, Manufacturing Effectiveness, Product Development Process Performance, and Value to Customer) are validated using confirmatory factor analysis. Validation of the various measurement scales is essential for future studies. The validation also provides a practical tool (a short questionnaire) and a set of benchmark measures to monitor the CAD usage, i.e., to provide insight into how CAD technology is employed, and whether it is utilized efficiently.

The relationships between the constructs are tested using structural equation modeling (SEM). The results support the indirect positive impact of effective CAD utilization on the various firm performance measures. The proposed research model suggests there are untapped opportunities for firms to better leverage their CAD technology. In other words, firms may have focused on the non-technical adaptations more than the technical adaptations, and were not able to take full advantage CAD. It may be a better approach to leverage the CAD technology, as suggested in the alternate model, by making the non-technical adaptations that support technology-enabled processes. In addition, a preliminary analysis regarding the impact of contextual variables on the relationships between the five constructs of interest is also presented.

Acknowledgements

I am very grateful to Drs. Mark A. Vonderembse, Jeen S. Lim, Dale J. Dwyer, and Phillip White for their involvement -- their wise counsel, prompt feedback, and personal commitment -- as chair and committee members that made this dissertation possible.

I am very appreciative of Cindy Sherette (formerly of the MBA office, now in the Office of Research) for her help and friendship over the years.

I am appreciative of my colleagues at the College of Business and Economics at the University of Idaho. Their understanding and support were encouraging to me.

I am thankful to my entire family in Malaysia for their confidence in me. This knowledge drives my persistence in completing this program.

I thank my husband, Mike, for his unwavering understanding and support throughout the years, with a special gratitude for his help in proofreading the many versions of my writing.

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Chapter 1. Introduction

Competition today requires each firm to procure and apply resources to create value by offering products and services that are of high quality in a timely manner and by continually improving its efficiency (Doll & Vonderembse, 1991; Davis, 1993; Roth, 1996; Gilmore & Pine, 1997). Firms pursuing these objectives must emphasize faster product development, shorter manufacturing cycles and quicker delivery times (Takeuchi & Nonaka, 1986; Stalk, 1988 &1990; Wheelwright & Sasser, 1989; Shilling & Hill, 1998) and employ computer-based technologies for efficiency and to minimize the detrimental effects of spatial and physical boundaries in supporting their business processes.

Firms persist in emphasizing product design and product development as a means of competing. Burcher and Lee (2000) made this inference based on the sizable investment in CAD software (second only to MRP) by manufacturers in the United Kingdom. Furthermore, Sun (2000) found that manufacturers in 18 countries ranked CAD as the most used among 16 advanced manufacturing technologies, and that CAD usage is expected to increase in the near future.

The use of CAD has been associated with a decrease in the time it takes to bring new products to market (e.g., Fitzgerald, 1987; Bull, 1987; Manji, 1989; Frangini, 1990; Teresko, 1990), improvement in the quality of the products developed (e.g., Crombez, 1988; Eade, 1988; DeMatthew, 1989; Velocci &

Childs, 1990), and cost reductions in developing products (e.g., Smith, 1982; Dutton, 1986; Fitzgerald, 1987; Lansiaux, 1987; Krouse, Mills & Potter, 1989).

Nevertheless, researchers focusing on CAD have found “gaps” in the impact accrued. These gaps represent discrepancies between the expectations and the actual realization of goals targeted when implementing CAD. They may appear as: (1) a delay in achieving targeted goals or achievement of less than targeted goals (Symon & Clegg, 1991; Beatty, 1992), (2) non-achievement of major goals (Symon & Clegg, 1991), and/or (3) unmeasurable achievement due to vague, obsolete or unrealistic goals (Beatty, 1992).

Many conclude that the ineffective use of CAD contributes to the gaps experienced. Some offer no explanation for CAD's ineffectiveness (Beatty & Gordon, 1988; Symon & Clegg, 1991; Beatty, 1992 & 1993). Some contend that limited utilization is a reason for CAD's ineffectiveness (Buxey, 1990; Dvorak & Kurland, 1995; Liker, Fleischer & Arnsdorf, 1995; Rendall, 1999). Others attribute CAD's ineffectiveness to managerial failure in understanding CAD's full potential, which consequently leads to failure to plan and adapt suitable organizational and technical systems (Adler, 1989; Twigg, Voss & Winch, 1992).

It is also plausible that the shortcomings in benefits accrued from CAD utilization lie within its appraisal. In appraising the financial impact of advance manufacturing technology (AMT) and information technology (IT), Kaplan (1986) and Porter (1992) warn that appraising the benefits of technology using conventional techniques such as payback method and return on investment are inadequate in accounting for the intangible effects of technology. Tangible benefits usually can be readily measured, but intangible benefits (e.g., improved efficiency, enhanced coordination, and increased creativity) are more difficult to quantify. In addition, the apparent time lag between the investment and the benefits accrued (Boyer, 1999; Sun, 2000) makes the timing of the appraisal an added consideration. Atkinson (1999) contends that measuring the benefits accrued by the traditional criteria -- cost, time, and quality -- are inadequate. Hence, many firms forego formal post-implementation evaluation of their technological investments because this process can be a costly exercise (Burcher & Lee, 2000).

The present research proposes to assess the impact of how CAD is used (CAD USAGE) on various facets of performance at the firm level of analysis. Academics and practitioners claim that the real productivity gains of CAD come from truly integrating CAD throughout the company, as well as with customers and suppliers (e.g., Adler, 1989; DeMatthew, 1989; Liker et al., 1995; Prabhaker, Goldhar & Lei, 1995, Briton, 1996; Chamberlain, 1998). There has been little large-scale empirical research performed to validate utilizing CAD in this manner.

The present study's research framework proposes that:

- Product Development Practices are antecedent to CAD USAGE, Manufacturing Effectiveness and Product Development Process Performance;
- CAD USAGE is antecedent to Manufacturing Effectiveness and Product Development Process Performance;

- Manufacturing Effectiveness is antecedent to Product Development Process Performance and Overall Firm Performance; and
- Product Development Process Performance is antecedent to Overall Firm Performance.

The inclusion of two intermediate operational performance impact (Brandyberry, Rai & White, 1999) constructs, Manufacturing Effectiveness and Product Development Process Performance, and one strategic level construct, Overall Firm Performance, in the model permits any time lags in the benefits accrued to be captured.

1.1 Problem Statement

What is the post-implementation impact of CAD? Assessing the impact of CAD is difficult when few reliable and valid measurement instruments are available to measure its utilization, and only traditional performance criteria -- cost, time, and quality -- are used.

Major research work on CAD has focused on either the adoption issues (Beatty & Gordon, 1988) or the implementation issues of CAD (Loung & Marsh, 1986; Adler & Helloloid, 1987; Adler, 1990; Buxey, 1990; Symon & Clegg, 1991; Beatty, 1992; Robertson & Allen, 1992; Twigg, Voss & Winch, 1992; Beatty, 1993; McDermott & Marucheck, 1995). Also, previous research has utilized either the case study methodology of prime users of CAD such as manufacturers of printed circuit boards or PCBs (Lee, 1989; Adler, 1990; McDermott &

Marucheck , 1995) or the field research methodology involving a small number of firms (e.g. Beatty & Gordon,1988; Buxey, 1990; Symon & Clegg, 1991; Beatty, 1992 & 1993; Scarso & Bolisani, 1996).

Few studies apply the survey methodology in measuring the utilization of CAD. Lefebvre and Lefebvre (1988) measured the degree of penetration of computer technology in firms that used CAD/CAM. Liker et al. (1995) concluded that firms' consistently underutilize CAD, but did not report the measurement scale used. Tan, Doll, Ruppel, Nandkeolyar and Abella (2001) developed a multi-dimensional scale to measure how firms utilize CAD based on an adaptation of Doll and Torkzadeh's (1998) work and Baba and Nobeoka's (1998) contention that the use of CAD in product development has evolved from improving the efficiency of drawing to concurrent engineering.

Previous studies evaluated the effectiveness of CAD/CAM integration in terms of achievement of pre-set goals (e.g., Adler & Helloloid, 1987; Beatty & Gordon, 1988; Marjchrzak & Salzman, 1989; Buxey, 1990; Beatty, 1992; Beatty, 1993; Youssef, 1993). The goals include reduced cost, improved quality, reduced development cycle time, improved efficiency, superior product performance, creative design or innovation, increased flexibility, and speedier customer service or responsiveness to customer. In striving to achieve pre-set goals, firms must undergo cycles of adaptations to the technology installed -- especially during the first three years (Tyre & Orkilowski, 1993). Adler and Helloloid (1987) propose that a firm must prepare itself in terms of creating or acquiring personnel with the experience and skills, planning and instituting procedures to promote coordination between manufacturing and engineering functions, providing strategic commitment and supportive organization structure, and fostering a culture of cooperation and learning to be successful.

Previous research (Boddy & Buchanan, 1984; Jaikumar, 1985; Markus & Robey, 1988; Weick, 1990; Delone & McLean, 1992; Sethi & King, 1994; Doll & Torkzadeh, 1998) suggests that utilization is antecedent to the achievement of impact, there are several levels of impact, and the achievement of impact across these levels is progressive (i.e., the various levels of impact can occur concurrently and need not be linear).

1.2 Research Questions

This research attempts to answer the following research questions:

1. Do product development practices drive the effective use of CAD, enhance manufacturing effectiveness, and improve product development process performance?
2. Does effective use of CAD increase manufacturing effectiveness and product development process performance?
3. How does manufacturing effectiveness and product development process performance relate to overall performance in terms of value to the customer?

1.3 Contributions of this research

This research explores the impact of CAD via the variance approach. A comprehensive research model for evaluating the antecedent factors to effective CAD usage and several performance measures (manufacturing effectiveness, product development process performance, and overall firm performance) is presented.

Theoretical contributions include assessment of the validity of measurement scales for each construct adapted from previous research. Also, relationships between the five constructs (Product Development Practices, CAD USAGE, Manufacturing Effectiveness, Product Development Process Performance, and Value to Customer) depicted in the proposed research model will be examined by employing the structural equation modeling (SEM) technique.

A preliminary assessment based on several contextual factors suggested in previous research as potential control variables (e.g., firm size, industry, and type of firm, i.e., make-to-stock versus make-to-order) can provide some insight into the direction of future research.

Practical implications include providing managers with a tool to measure the benefits of CAD accrued over time, an industry benchmark, and an understanding of antecedent factors to achieve better performance. With an enhanced understanding of the impact of CAD and an industry benchmark, it will be easier for a firm to identify its optimal CAD use, and to target its improvement efforts such that it achieves this optimal use.

Chapter 2. Literature Review, Model and Hypotheses Development

This research focuses on a specific technology, CAD, for three reasons. First, many firms utilize CAD. Youssef (1993) found that 93% of his sample of 165 firms with SIC codes 34, 35, and 36 have CAD. Chen and Small (1994) found that 90.4% of their sample of 94 manufacturers in the United States with annual sales over $5 million have CAD. Burcher and Lee (2000) found CAD to be a software in which UK manufacturers frequently invest. Sun (2000) found CAD was the most used technology in comparison with fifteen other advance manufacturing technologies by manufacturers from 18 countries, and that the utilization of CAD is expected to increase in the next three years.

Second, CAD has been widely adapted to various industry-specific needs. Numerous research efforts have focused on industry-specific adaptations of CAD such as appliance, furniture, fashion, and ceramics applications (Hu & Teng, 1996; Scarso & Bolisani, 1996; Chua, Gay & Hoheisel, 1997a & 1997b; Posledni, 1997; Chamberlain, 1998; Weldon, 1999; Dickson & Coles, 2000). Therefore, the utilization of CAD is expected to increase as more industries find it a viable technology.

Third, CAD has undergone tremendous technical advancements. The capabilities embedded in the CAD technology today offer many additional opportunities for building competitive advantage. In conjunction with the availability of increasingly affordable computing power in hardware (Faries, 1997), parametric modeling capabilities now permit complex geometric computations to be handled with ease. Enhancing the manipulation of unambiguous (3D solid) models serves to promote greater use of 3D solids, which subsequently can become a source of data for building product data management (PDM) systems and leveraging enterprise-wide integration (Beckert, 1994; Deitz, 1997; Wiebe, 1997).

In spite of the popularity of CAD and its continuing advances as a component of advance manufacturing technology, a review of the CAD and CAD/CAM literature, as discussed in the next section, indicates a comprehensive empirical research model concerning the impact of CAD has yet to be developed.

2.1 CAD and CAD/CAM Literature Review

The major organizational level research pertaining to CAD and CAD/CAM is summarized in Table 2.1 (three pages). This literature is analyzed along three criteria: (1) stage of assimilation, (2) methodology, and (3) research framework.

2.1.1 Stage of Assimilation

Most of the CAD and CAD/CAM literature shown in Table 2.1 have focused on adoption and implementation issues and do not address the problem of achieving the full use of CAD. Assimilation of CAD takes time, as much as 10, 20 and even 30 years (Gross, 1995). In the adoption stage studies, issues are addressed assuming that having CAD implies that it will be used. In the implementation stage studies, issues are addressed assuming that using CAD implies it will be used effectively.

2.1.2 Methodology

Many CAD and CAD/CAM research efforts employ the process (intepretist) approach. This approach generates rich observations concerning the critical historical events impacting the use of CAD (Loung & Marsh, 1986; Adler, 1989 & 1990; Robertson & Allen, 1992) and the effects of using CAD (Buxey, 1990; Symon & Clegg, 1991; Robertson & Allen, 1993). These research efforts are most critical to develop our understanding of the utilization of CAD during initial periods after CAD is adopted. This approach often involves qualitative observations of the dynamics between organizational culture, strategy, structure, procedure, and skills (Adler, 1989) within the context of the socio-political environment (Lee, 1989) of the firm. If any quantitative measures are employed in this research approach, they typically are not reported.

2.1.3 Research Framework

The adoption stage research suggests that the success/failure of the CAD implementation stage is dependent on the resolution of adoption issues. Resolution of these issues (selecting the CAD system, specifying the target goals, choosing the implementation strategy, and planning for technical and non-technical change) promotes the development of specific organizational

Table 2.1: Summary review of major organizational level CAD and CAD/CAM research

Author(s)	Date	Stage of Assimilation	Research Methodology	Measurement Instrument	Research framework	
					Dependent Variable	Independent Variables(s)
Gagnon & Mantel	1987	Adoption	Case Study: Six firms in SICs 35 & 37	N/A	Perceived Improvement in firm performance (total number of labor hours needed to complete successive similar projects).	Strategy selected to obtain CAD technology
Beatty & Gordon	1988	Adoption	Case Study: Survey more than 200 managers & operating-level employees in 10 Canadian firms	N/A	Success of CAD/CAM integration	Three types of barriers: Structural, Human & Technical factors
Luong & Marsh	1986	Implementation	Case study: A defense equipment firm (Advance Engineering Laboratory)	N/A	Effectiveness of CAD/CAM integration	4 components to integration strategy: hardware/software, databases, organizational structure & personnel integration
Adler & Helloloid	1987	Implementation	Conceptual paper	N/A	Effectiveness of CAD/CAM integration (propose the use of changes induced by CAD/CAM efforts in effective product development projects)	Preexisting organizational conditions: skills, procedures, structure, strategy, and culture.
Lefebvre & Lefebvre	1988	Implementation	From 5900 Canadian firms surveyed, 152 CAD users, 1154 non-CAD users responded.	Defined but not reported. Validation of measure also not reported.	Workforce's productivity & number	CAD users vs. non-CAD users
Adler	1989	Implementation	Conceptual paper developed from observing 9 electronics and 4 aircraft companies in the U.S.	N/A	Effectiveness of CAD/CAM integration	Managerial challenges and research issues at five key levels of organizational learning (skills, procedures, structure, strategy, and culture).
Lee	1989	Implementation	Case Study: 7 firms	N/A	Changes in work organization	Managerial implementation strategy and contextual factors: pressure to adopt, socio-political environment of the firm.

Adler	1990	Implementation	Case Study of "best practices firms": 11 firms (9 electronics and 4 aircraft companies in the U.S)	No	Effectiveness of CAD/CAM integration	Workforce's skills
Buxey	1990	Implementation	Case Study: 8 Australian firms	N/A	Impact of CAD/CAM on manufacturing (productivity, high variety production, better-made products)	Firm context in using CAD/CAM
Symon & Clegg	1991	Implementation	Action research study over a period of 18 months at a firm in the light engineering industry during its CAD/CAM implementation stage.	Surveys were specific to the context of the case firm.	Firm Performance (achievement of objectives)	Technology-led change (technological issues are considered first, human and organizational issues are considered later)
Beatty	1992	Implementation	3-year longitudinal Case Study: 10 Canadian firms	N/A	Success of CAD implementation (judged based on the firms' achievement of pre-set goals after 3-year period)	Critical success factors: Skilled champion, system integration & organizational integration
Robertson & Allen	1992	Implementation	Case Study: 10 firms	N/A	How CAD is use in design-engineering process (electronic drafting boards; engineering support tool; communication tool) and benefits accrued from CAD use (productivity, effective communication; changes in engineering work; improve coordination)	Managerial perception of CAD (Physical Capital, Human Capital or Social Capital)
Twigg, Voss, & Winch	1992	Implementation	Case Study: 15 firms	N/A	Effectiveness of CAD/CAM Integration	Non-technical or Managerial linkage mechanisms
Beatty	1993	Implementation	3-year longitudinal Case Study: 10 Canadian firms	N/A	Success of AMT projects (gauged based on how closely pre-set goals were realized in a 3-year study period)	Implementation decisions: pace, component, champion, team structure & job redesign

Robertson & Allen	1993	Implementation	Survey 75 engineers in 2 gas turbine manufacturing firms.	N/A	Engineering performance (based on number of engineering change attributable to an engineer's work 3 months after the completion of a design)	Three types of CAD use in engineering work (design, analysis, and communication)
Liker, Fleischer & Arnsdorf	1995	Post-implementation	Interviews, site observations, and survey 10 sites of 6 heavy CAD user firms (Fortune 100 companies)	Survey instrument was not reported.	Lack of realizations of CAD benefits	Underutilization of high-level features due to lack of both technical and organizational integration.
Baba & Nobeoka.	1998	Post-implementation	Conceptual Paper with case illustration	N/A	Improve efficiency and "creativity"	3D CAD capabilities
Kappel & Rubenstein	1999	Post-implementation	Conceptual Paper	N/A	Improve creativity and coordination	Ideation and optimization

* Unless specified as best practice or heavy user firms, case study methodology utilized firms that are not unique.

contextual factors, which facilitates the implementation of CAD (Beatty & Gordon, 1988).

Much CAD/CAM research discusses the importance of contextual factors and relates the organizational contextual factors to the firm's performance (Loung & Marsh, 1986; Beatty & Gordon, 1988; Adler & Helleloid, 1987; Adler, 1989 & 1990; Symon & Clegg, 1991; Twigg et al., 1992). Some researchers group the organizational contextual factors as technical and non-technical, and allude to the relative importance of these two types of organizational contextual factors to firm performance (Adler & Helleloid, 1987; Adler, 1989 & 1990; Symon & Clegg, 1991; Twigg et al., 1992). A few suggest a relationship between organizational contextual factors and utilization (Robertson & Allen, 1992; Liker et al., 1995; Baba & Nobeoka, 1998; Kappel & Rubenstein, 1999). One empirical study links utilization to performance (Robertson & Allen, 1993).

Typical performance measures are the achievement of pre-set goals (Beatty & Gordon, 1988; Symon & Clegg, 1991; Beatty, 1992 & 1993) or the achievement of product development goals (Adler & Helloloid, 1987; Adler, 1990). Several studies evaluate the impact of CAD on workforce changes (Lefebvre & Lefebvre, 1988, Lee, 1989). Others focus on the performance of specific functions, e.g., the impact on manufacturing (Buxey, 1990) and engineering work (Robertson & Allen, 1992). Recent conceptual pieces recommend using process measures such as improved creativity, efficiency and coordination (Baba & Nabeoka, 1998; Kappel & Rubenstein, 1999).

To better understand the impact of CAD, a theoretical framework -- depicting the antecedents and consequences of utilizing CAD, based on a comprehensive literature review, is discussed in the next section.

2.2 Theoretical Model

The research model presented in Figure 2.1 shows the proposed relationships between the five major constructs of interest. The numbers next to each link correspond to the nine hypotheses to be developed in later sections.

The five constructs in the model include: (1) Product Development Practices: *Concurrent Engineering*, *Supplier Involvement*, *Customer Involvement*, *Heavyweight Product Development Managers*, and *Platform Products* (Koufterous, 1995); (2) CAD USAGE: *Engineering Design Usage*, *Cross Functional Usage*, *Integrate with Customers Usage*, and *Integrate with Suppliers Usage* (Tan et al., 2001); (3) Manufacturing Effectiveness (Tracey and Vonderembse, 2000); (4) Product Development Process Performance - *Team Process Outcome and Team Efficiency* (adapted from Hong's (2000) *Time-to-Market* and *Development Productivity*); and (5) Value to Customer (Tracey, 1996; Tu, 1999). A comprehensive list of the literature base for each construct has been presented in the respective citations, and the definition for each construct is summarized in Table 2.2.

The rationale underlying the theoretical framework can be summarized in four phases as described in the ensuing sections.

Figure 1: Proposed Theoretical Model

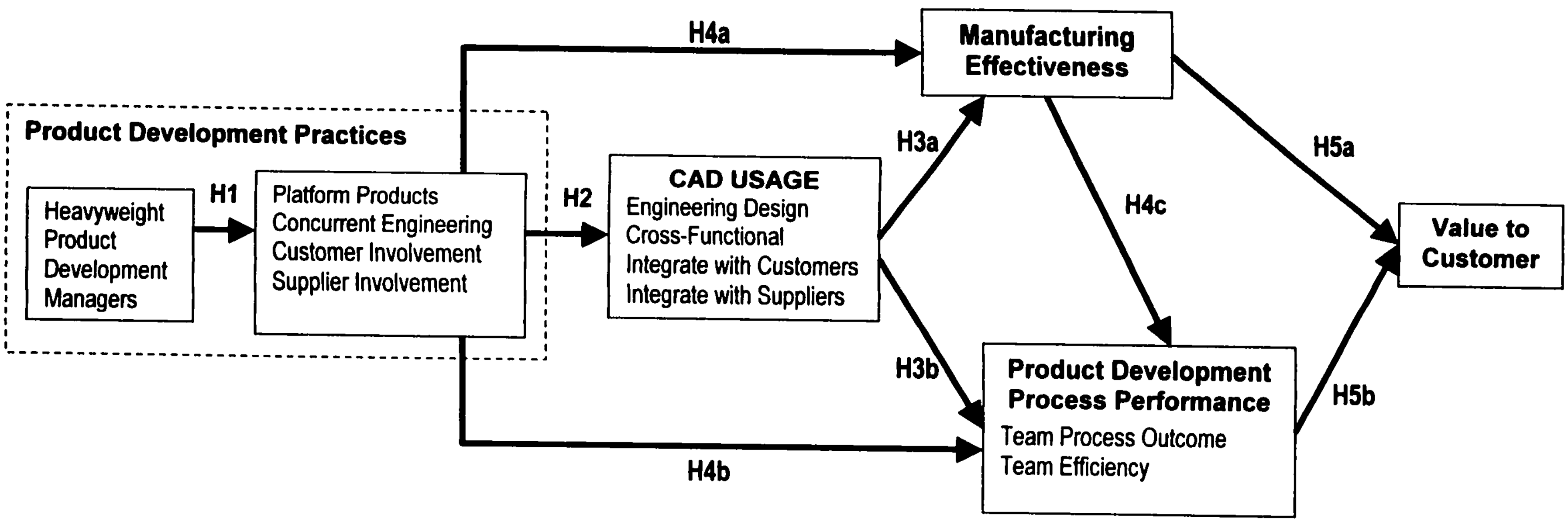


Table 2.2: Construct Definitions

Construct	**Definition**
Product Development Practices	The extent to which a firm employs concurrent engineering, customer involvement, supplier involvement, product platform practices, and the clout of its heavyweight product development managers.
CAD USAGE	The extent to which CAD is used to (a) evaluate and analyze alternative designs for a product, and to facilitate exchange of design ideas among product engineers, (b) provide support files/data/prints to manufacturing and other functions within the firm, and (c) enhance communications regarding product specifications with customers and component suppliers.
Manufacturing Effectiveness	The extent to which manufacturing function is able to control production cost without sacrificing product quality in meeting their customers' need.
Product Development Process Performance	The extent to which the product development team's work is timely and efficient (productive).
Value to Customer	The extent to which customers perceived a firm's product as having high value and their degree of satisfaction with the products.

Phase 1: Effective use of CAD depends on the pre-existing product development practices.

Koufteros (1995) identified six practices as dominant drivers of time-based product development, one being computer usage. In a later study, Doll, Koufteros and Vonderembse (1997) presented five practices (heavyweight product development managers, concurrent engineering, platform products, customer involvement, and supplier involvement) as antecedents to information technology usage. Furthermore, firms with high levels of information technology usage tend to achieve high levels of product innovation (Koufteros, Vonderembse & Doll, 2000). Specifically, concurrent engineering and platform product practices are key management practices as far as the firm's utilization of information technology, and heavyweight product development managers drive these key management practices.

CAD specific research suggests the achievement of a hierarchical progression in the levels of usage is dependent on the prevailing conducive context. Robertson and Allen (1992) contend that the three possible ways of using CAD (physical capital, human capital, or social capital) require an inclusive scale of three enablers: a basic enabler -- training, support, hardware and software, ease of use, and usefulness; a human support enabler -- management's understanding of CAD, 3D usage, and simplified links to analysis; and a coordination enabler --mandated use of CAD, moving the official design document onto CAD, maintaining one model, adding intelligence to the design, use of CAD file naming convention, standardized use of levels, network transparency, and the presence of CAD design review room.

Adler and Helloloid (1987) view the hierarchy of progressively broader and deeper CAD/CAM integration as consisting of: (1) downloading data directly from CAD database to the manufacturing environment, (2) inclusion of manufacturability design rules, criteria, and models in the CAD database, (3) inclusion of automatic manufacturing process planning, and (4) error recovery capabilities. They assert that the organizational context is more likely to dictate the pace of CAD/CAM integration than the technical context. Specifically, the more appropriate skills, procedures, strategies, and culture that are in place before a given phase of integration, the greater CAD/CAM integration (Adler & Helloloid, 1987; Adler, 1989 &1990).

Liker, Fleischer and Arnsdorf (1995) propose five levels of CAD features -- automation of routine tasks, 3D, electronic transfer of the design database to manufacturing, electronic transfer to engineering analysis and simulation, and a paperless link with customers and suppliers. They conclude that an extensive division of labor, and a high degree of fragmentation and segmentation of knowledge and skills in the design process prohibit the effective utilization of CAD.

Several studies suggest that effective utilization of computer-based technology is not a question of *how much* but rather an issue of *how* which leads to a consideration of breadth, depth, and scope of utilization -- e.g., Doll and Torkzadeh (1998) on general computer usage; Rai and Howard (1993) on computer-aided software engineering (CASE) technology; and Masseti and Zmud (1996) on electronic data interchange (EDI) technology. Tan, Doll, Ruppel, Nandkeolyar and Abella (2001) developed a multidimensional scale on *how* CAD is utilized incorporating the hierarchical relationship as proposed by Robertson & Allen (1993), Adler & Helloloid (1987) and Liker et al. (1995).

Phase 2: Improving manufacturing effectiveness requires time-based product development practices and effective CAD use.

Manufacturing strives to control production costs without sacrificing product quality. Effective planning and controlling of the operations at the production floor is essential to achieving efficient manufacturing system. It entails keeping rework, material handling and production costs low, increasing outgoing product quality, reducing the levels of work in progress, and meeting delivery deadlines (Tracey & Vonderembse, 2000).

Product development practices ensure that products are manufacturable using the resources (equipment, tools, operator skills, etc.) available as much as possible (Adler, 1995) and at a reasonable cost (Tu, 1999). During the product development process, collaborative discussions between cross-functional team members, suppliers, and customers in iterations of defining and refining, and ultimately the creation of the design of a product can result in simplification and streamline of the manufacturing process, parts that are easier to assemble, simpler and quicker setups for production, and reduction in the number of parts per product – i.e., improve product manufacturability (Swink, 1999).

Using CAD as the formal design medium, theoretically, requires each engineering change (EC) during a product development process as well as each accepted engineering change order (ECO) during the actual production to be documented and the relevant CAD files appropriately updated. An EC or ECO is generated either to correct an error or problem, or in response to a market-driven feature change (Terwiesch & Loch, 1999). It can be as simple as documentary amendments or as complicated as the entire redesign of products and manufacturing processes (Huang & Mak, 1999).

Typically, during the product development process many of the issues identified and resolved pertained to design-for-manufacture and design-for-assembly (Nevins & Whitney, 1989). Some can be consistently eliminated via implementation of design algorithms when CAD is used to create the evolving product design. Others can be resolved using computer-aided engineering (CAE) analyses. Therefore, a product development team that uses CAD to make modifications expeditiously, incorporates proven designs of parts or components (developed in-house or by parts/components suppliers), and adheres to a product platform strategy will maximize commonality of many parts to easily create customized product designs. This allows manufacturing to economically accommodate a large number of product varieties across generations of products.

Greater commonality in a variety of products reduces the total number of parts, components, and tools that manufacturing must manage (Baker, Magazine & Nuttle, 1986; Gerhack & Henig, 1986; Eynan, Rosenblatt, 1996; Perera, Nagarur & Tabucanon, 1999). Common parts and components allow manufacturing to consolidate production requirements using an accurate bill of material (BOM) that includes material and engineering specifications information. Both BOM and specifications are derived directly from the design of the product (i.e. the CAD files). Fewer parts, components, and tools means fewer parts, components, and tools inventory, and reduced total amount of work-in-progress inventories for manufacturing to manage.

Phase 3: Improving product development process performance requires time-based product development practices, effective CAD use, and effective manufacturing.

Hong (2000) found the level of knowledge integration significantly influences the product development process (i.e., the performance of product development teams). A fundamental premise of time-based product development practices is that product development is a team-oriented activity. Concurrent engineering specifically states that a team must consist of cross-functional members, it is formed early in a product development project, and that members work on product and process designs simultaneously. Involving suppliers and customers as team members in product development further enhances the opportunity for concurrent developments. In bringing people with variant priorities together, these three practices (concurrent engineering, customer involvement, and supplier involvement) are mechanisms for knowledge integration. Therefore, time-based product development practices have positive impact on the product development process performance (i.e., improved teams' ability to meet time-to-market schedule and increased development productivity).

CAD utilization can also be a mechanism for knowledge integration. CAD acts as a common language that enhances communication and coordination between different component designers, as well as between engineers from multiple functions, e.g., design, manufacturing, analyses and experimentation (Robertson & Allen, 1992). Baba and Nobeoka (1998) suggest that the communication value of CAD, especially advanced 3D systems, can play a central role in the creation of knowledge-based product development systems. Therefore, the utilization of CAD affects the timeliness and effectiveness of product development teams.

A generic product development process consists of five stages: product concept, system design, detail design, testing and refinement, and manufacturing production (Ulrich & Eppinger, 1995). During the last two stages, product development teams' timeliness and effectiveness are linked to the manufacturing function. During the testing and refinement stage, a small batch production of prototypes may be required. An effective manufacturing system will likely have the capacity and the flexibility to insert the production of prototypes as needed into the planned production schedule without adversely affecting its ability to deliver the planned productions in a timely manner. During the manufacturing production stage, an effective manufacturing system will schedule planned productions to meet market introduction deadlines and have high adherence to the planned production schedules. Hence, manufacturing effectiveness affects the product development process performance.

Phase 4: Creating higher value to customers is achieved through excellence in product development process performance and manufacturing effectiveness.

As markets become increasingly segmented and product life cycles shorten, firms must cater to individual customer's needs (Doll & Vonderembse, 1991; Goldhar, Jelinek & Schlie, 1991). It is not sufficient to focus on market share, businesses need to shift focus to customer share – attracting as many customers as they can, and then selling them more products (Peppers & Rogers, 1997). In other words, firms must emphasize building relationships with their customers.

A key strategy to increasing customer share is creating customer value through excellence in the product development process and the manufacturing of products (Gilmore & Pine, 1997). Customer value may include factors such as satisfaction with product quality, variety, price, feature, performance, and the services associated with the delivery of the products. Excellent performance in the development process aids in the quicker delivery of a variety of product designs – i.e., meet customer demand across a spectrum of features, performance, and quality -- to manufacturing. Excellence in manufacturing will ensure that the transformation of the designs into actual products occurs and that the finished goods are delivered in accordance to promised schedules (Hayes & Pisano, 1994).

The following sections will review the literature pertaining to each of the five constructs in the theoretical model, and the nine research hypotheses are developed.

2.2.1 Product Development Practices

Koufteros (1995) examined the product development process literature and found that in addition to computer usage (DeMeyer, 1992; Rosenthal & Tatikonda, 1992; Sanderson, 1992), five other practices support time-based competition. Implementing these inter-related practices in a coherent manner is necessary to achieve lean product development (Karlsson & Ahlstrom, 1996). They are: heavyweight product development managers (Clark & Fujimoto, 1991; Wheelwright & Clark, 1992), platform product (Wheelwright & Sasser, 1989; Clark & Fujimoto, 1991; Wheelwright & Clark, 1992), concurrent engineering (Takeuchi & Nonaka, 1986; Clark & Fujimoto, 1991; Susman & Dean, 1992), supplier involvement (Imai, Nonaka & Takeuchi, 1985; Clark, Chew & Fujimoto, 1988; Hartley, Zirger & Kamath, 1997; Hartley, Meredith, McCutcheon & Kamath, 1997; Handfield, Ragatz, Petersen & Monczka, 1999; McGinnis & Vallopra, 1999), and customer involvement (Whybark, 1994; Murakoshi, 1994).

Heavyweight Product Development Managers measure the extent to which senior executives with substantial expertise, informal influence, and formal decision-making authority champion and direct the development efforts.

According to Clark and Fujimoto (1001), it reflects the organizational empowerment of these managers regarding the firm's product development endeavors. Heavyweight product development managers' authority to override functional managers allows them to accomplish much – the championing of project/innovation (Maidique, 1980; Beatty & Gordon, 1988), organizing and tracking the progress of the project development teams, and reducing the number of cumbersome approval procedures. This enhances cross-functional and hierarchical effectiveness.

Platform Products is defined as the extent to which a variety of products are derived from small and frequent innovations to basic product platforms. The advantage of developing products as "platforms" is the expedited time to market of future product derivatives (Wheelwright & Sasser, 1989; Wheelwright & Clark, 1992; Koufteros, 1995; Doll et al., 1997). A platform product is used multiple times by making small incremental alterations and enhancements to produce variant products and create a range of new product offerings in quick succession. In this manner, the basic-core product "evolves" to make the most of opportunities in the marketplace, increasing returns by decreasing the marginal development costs of families of products (Arthur, 1989).

Concurrent Engineering is defined as the extent to which product and process designs are generated concurrently from the early stages of the product development process by cross-functional teams. Concurrent product and process design reduces lead times in product development (Imai, Nonaka & Takeuchi, 1985; Clark & Fujimoto, 1991). The use of cross-functional teams has been recognized as a tool for accelerated product development (Crawford, 1992; Herstock, Cowman & Peters, 1994). The benefits of cross-functional teams stem from enhanced communications and organizational learning (McKee, 1992). Osborn (1957) and Donnellon (1993) suggest that teams produce more creative solutions, make better decisions (Davis, 1973), improve implementation of decisions, and increase commitment (Cohen & Ledford, 1991). Early involvement of essential functions in the product development process of a firm provides greater opportunities to address various perspectives, ideas, concerns and problems as the designs evolve (Stalk & Hout, 1990). Essentially more work is performed in the earlier stages of the product development process so as to allow greater productivity gains downstream (Buxey, 1990; Robertson & Allen, 1992).

Supplier Involvement is defined as the extent to which suppliers provide input as product development team members and/or perform the development of components (parts or subassemblies) of a product. Suppliers can play an important role in the product introduction race. Problems with vendors can lead to delays in product introduction (Wilkes & Norris, 1972; Hartley, Zirger & Kamath, 1997), while improved relations with vendors can result in the improved speed of product introductions (De Meyer & Van Hooland, 1990; Mendez & Pearson, 1994; Handfield & Pannesi, 1995; McGinnis & Vallopra, 1999). Briton's (1996) report on supplier partnering practices (visits to participate in development, input on product plans, inter-operate CAD systems, reciprocal sharing of strategic and product planning, and on-site presence for collaboration) finds that greater supplier involvement in the product development process can result in fewer cancelled product developments, fewer incidents of schedule slippage and fewer changes to product features.

The supply chain management literature (Cooper, Lambert & Pagh, 1997) views the preceding suppliers and succeeding customers as interdependent links, and emphasizes sharing of information upstream and downstream across the linkages as critical to a smooth product flow along the value-added chain. With the increasing emphasis on JIT philosophies, suppliers' goals are becoming increasingly intertwined with their customers' (the original equipment manufacturers' or OEMs') goals. This trend has given rise to the concept of preferred suppliers, where OEMs limit the number, tighten the management, and implement quality certification programs regarding their supplier base. Preferred suppliers are classified as 1st tier, 2nd tier and 3rd tier in correspondence to the range of their capabilities. The preferred status often reflects the position of a supplier in the value added chain. The lower the preferred status of a supplier, the further upstream it is from the OEM, and the later and lesser extent of involvement in the OEM's product development. The higher the preferred status of a supplier, the closer upstream it is to the OEM, and the earlier and greater extent of involvement in the OEM's product development.

The first tier suppliers perform the entire development of a component -- including time-consuming testing and specification conformance approvals (Schriefer, 1995). They are portrayed as partners in product development from the early concept stages of design (Liker, Kamath, Wasti & Nagamichi, 1996). On the other end of the classification, third tier suppliers provide manufacturing expertise input to an OEM's product development team upon solicitation (Ansari & Modarress, 1994). Typically, they are responsible for producing specified components where the design of components has been completed. These two forms of participation -- input and development -- are combined in Koufteros's (1995) construct of supplier involvement.

Customer Involvement is defined as the extent to which customers are active product development team members. Managing the flow of information in the product development process across a value chain that includes the customers has been recognized as an important part of doing business (Ettlie, 1997). Larsson and Bowen (1989) considered customer participation as a major source of reducing input uncertainty. Von Hippel (1986) asserts lead users (customers) are a source of novel product concepts. Iansiti and MacCormack (1997) contend flexible product development is rooted in the ability to continually sense the market changes, test technical solutions, and integrate customer needs with technical solutions. In turbulent business environments, they illustrate opportunities for involving internal and external customers in testing (broad internal testing, testing by lead users, and broad consumer testing) the evolving product throughout the product development process. When technology, product features, and competitive conditions are predictable or evolving slowly, quality function deployment (Hauser & Clausing, 1988) serves as an adequate framework for internalizing customers' input.

Theoretical and empirical studies suggest that collaboration with customers is a valuable way to achieve both innovation and economic success (e.g., Gemunden, Heydebreck & Herden, 1992; Gales & Mansour-Cole, 1995; Hakansson, & Snehota, 1995). Partnerships can shorten development time and reduce development cost because more innovative ideas may emerge from combining resources (Hakansson, 1987), and the manufacturer gains access to development capabilities it lacks in-house (Ruekert, & Walker, 1987; Athaide, Meyers & Wilemon, 1996). De Graaf and Kornelius (1996) argue that in the PCB (printed circuit boards) industry, an inter-organizational concurrent engineering approach to product development can further enhance the achievement of reduced throughput time, improved quality and lower costs when customers are also involved.

The above five time-based product development practices (heavyweight product development manager, platform products, concurrent engineering, supplier involvement, and customer involvement) used in this study are adopted from Koufteros (1995).

2.2.2 CAD USAGE

In product development, a CAD application can be used to design new products, modify existing products, and perform the required drafting. Often a new set of manufacturing tools (molds, dies, jigs, and fixtures) is required, and CAD can be used to design or modify the tools needed for production. The manufacturing layout for a new product may also be evaluated using CAD. With built-in computer aided engineering (CAE) capabilities, engineers can examine and test a CAD design -- product, tool, and layout -- from the structural and engineering viewpoint.

The most fundamental uses of CAD are associated with the fact that CAD automates some aspects of the engineering and design process.

- CAD performs tedious and routine calculations (Dring, 1994) and makes the task of drawing easier while maintaining highly accurate numeric computations.
- Design parameter databases can be created and incorporated into the CAD application (Mills, 1995), which enables additional engineering testing.
- CAD can easily generate numerical control programs (Mills, 1995) to reduce the setup time and programming errors of NC/CNC machines for manufacturing.
- CAD can provide realistic visuals in 3D and produce neat drawings/blueprints (Grubb, 1993) to accurately display product specifications and/or to prepare documentation for the production processes.
- Computer files can be manipulated -- retrieved, copied, modified or exported (DeMatthew, 1989; Omanoff, 1991; Puttre, 1993) -- which simplifies the designing task.

- CAD offers graphic simulation capability (Grubb, 1993; Suk, Noh & Choi, 1995) that allows visual inspection of fit and evaluation of mechanical design animation.

A multidimensional measure of CAD USAGE (Tan et al., 2001) -- Engineering Design Usage, Cross-Functional Usage, Integrate with Customers Usage, and Integrate with Suppliers Usage – is used in this study.

Engineering Design Usage is defined as the extent to which CAD is used to evaluate and analyze alternative designs for a product, and to facilitate exchanges of design ideas among product engineers. Product engineers work independently and with colleagues who influence the design (Kappel & Rubenstein, 1999) as each engineer may specialize along specific components of a product line and different engineers work on different components of the product. There are inherent interdependencies among the team members due to the boundary interactions between the components. Within the boundary and constraints of each component, each engineer has the creative freedom to innovate. An engineer often generates several alternative designs of a component and performs his/her own evaluations on these designs and, more often than not, formally as well as informally, consults with other engineers on the team to resolve or improve his/her design.

On the other hand, in some firms each engineer may also be associated with specific CAD systems (e.g., CATIA, ProE) and model formats (2D wireframe, 3D wireframe, 3D surface, or 3D solids). In this case, the design team is more likely to be working on different stages in developing a model of the product. Each engineer has great interdependencies with his/her immediate preceding and the succeeding stage. Each engineer must be cognizant of the requirements of the successive stages, and create his/her CAD model such that it does not introduce "glitches" (Hoopes & Postrel, 1999) for the ensuing engineers. Members of the design team typically discuss and share knowledge in determining the "best" design for the product before embarking on creating the CAD model. Difficulties encountered may prompt further discussion and sharing of knowledge and revision to the "best" design after the development of the CAD model is underway.

Cross-functional Usage is defined as the extent to which CAD is used to provide support files/data/prints to manufacturing and other functions within the firm. Beyond aiding the engineering design work, CAD can be used to enhance vertical and horizontal integration within the firm. CAD acts as a common language that enhances communication and coordination between different component designers as well as between engineers from multiple functions (e.g., design, manufacturing, analyses and experimentation). Baba and Nobeoka (1998) contend the communication value of CAD, especially advanced 3D systems, plays a central role in the creation of knowledge-based product development systems. Robertson and Allen (1993) found that conversations in front of a 3D CAD design are more effective because fewer misunderstandings occur. 3D provides the ability to visualize component details (e.g., back views, rounded corners) and to make quick changes by supporting communication between design and manufacturing engineers. Furthermore, the 3D data can be used directly by manufacturing engineers for the development and design of dies and molds. This translates into the ability to perform quicker (and frequent) data transfer from design to manufacturing.

Other functions such as Quality Control, Purchasing, and Marketing also derive communicative value from CAD. Innala and Torvinen (1995) assert that quality assurance with coordinated measuring machines (CMM) utilizes inspection programs, measuring programs, and tolerancing information that are generated from CAD geometry. Incorrect dimensioning and tolerancing in CAD design can result in engineering changes being generated at the production shop floor. Purchasing plays an important interfacing role between a firm and its suppliers (Cooper & Ellram, 1993). Purchasing personnel utilize the bill of material and material specifications (extracted from the product design) and the master production schedule to select suppliers and to schedule purchase order releases. Marketing is involved in soliciting sales of new products and servicing the after-market segment of the customers (i.e., providing services on the products sold). CAD models form a visual catalogue with all the technical information attached to serve Marketing's goal of promoting sales of proven products.

Integrate with Customers Usage and **Integrate with Suppliers Usage** are respectively defined as the extent to which CAD is used to enhance communications regarding product specifications with customers and suppliers. As a component of CIM, CAD is an important enabler for integration beyond the boundaries of a firm. Where digital technologies permit, compatible electronic files can be easily exchanged and copied, used and reviewed, revised and modified, and transferred and downloaded as needed. With an inexpensive means of relaying electronic files, the sharing of CAD files (via internet or EDI) with external customers and suppliers of the firm provides a way to exploit the expertise across networks of value-added activities that will substantially change the standard of competition with respect to speed and efficiency of product development (Baba & Nobeoka, 1998). Theoretically, a global production system with real time integration of worldwide development and production activities can be achieved through intensive use of IT.

Increasingly, companies are realizing that the exploitation of IT in design and product data management (PDM) is a prime source of competitive advantage (Cassells & Claxton, 1996). Forming closer ties via IT with suppliers is becoming a reality. For example, Ford has invested in a single integrated software system (Fowler, 1996) and introduced a product information management system to link CAD, CAE, and CAM into a global system of common data (Struebing, 1996). These data are made available to all automotive disciplines within Ford and its suppliers.

2.2.2.1 Research Hypothesis 1

Doll, Koufteros, and Vonderembse (1997) group the five product development practices into three classes of factors: internal context practices (heavyweight product development managers, platform products), internal integration practices (concurrent engineering) and external integration practices (customer involvement and supplier involvement). They propose a framework that displays antecedent relationships between the classes of factors as a predictor of computer usage in product development. They contend that the success of each factor is successively dependent on the preceding factor. More specifically, the work of Koufteros, Vonderembse and Doll (2000) concludes that firms with high levels of information technology usage tend to achieve high levels of product innovations and found heavyweight product development managers to be the driver of key management practices (concurrent engineering and platform product practices) to the firm's utilization of information technology. Hence,

Hypothesis 1: **Heavyweight Product Development Managers** have a positive effect on the firm's level of *Product Development Practices*.

2.2.2.2 Research Hypothesis 2

In managing and guiding project development efforts, heavyweight product development managers encourage the use of time saving tools such as CAD by acquiring the necessary resources, supporting user training, and promoting extensive use of the tools. Firms that promote the use of platform products to hasten the development of product variants, are more likely to use CAD in ways consistent with accumulating integrated systemized knowledge (Nobeoka & Cusumano, 1997; Baba & Nobeoka, 1998; Kappel & Rubenstein, 1999). Firms practicing concurrent engineering and concurrent development (Kappel & Rubenstein, 1999) are more likely to use CAD to support frequent, interactive, and rich communications between team members, with other teams and other functions of the firm.

Early supplier involvement in the product development process can be critical in resolving initial design issues (Hartley, Zirger & Kamath, 1997). Suppliers may suggest new ways of dealing with problems, provide technological contributions, and assist in quality assurance considerations. Suppliers can help identify material substitutes, the elimination of parts, process improvements, and assist in the development of faster and cheaper designs (Briton, 1996; Winter, 1996). For products primarily designed in-house, the OEM's utilization of CAD is expected to be more effective as more iterations of the evolving product designs are made to incorporate and test suggestions derived from the suppliers' involvement.

On the other hand, when the outsourcing of components to suppliers evolves from economic necessity into strategic partnerships in product development, suppliers acquire the responsibility for developing the components and share in the cost of quality of those components throughout the product's life cycle. As such, it becomes critical that quality is built into the conceptualization of each component of the entire product. Various suppliers working on different components must coordinate their own development efforts with those suppliers immediately affected by their designs. It is often necessary to negotiate the design parameter and to simulate the functionality of the interdependent designs developed by different suppliers. The primary concern of the OEM is to ensure that updated designs by different suppliers and the designs made by their own engineers, when put together in its entirety, conform to the product definitions. It is plausible that greater supplier responsibility for component development leads to an increase in richer forms of communications, afforded through CAD, between the suppliers without significantly affecting their volume of communications with the OEM (Hartley, Meredith, McCutcheon, and Kamath, 1997).

Design changes frequently occur in the product concept stage of the product development process. Often the changes initiated by the internal and external customers are improvements to a design rather than corrections of errors. Involving customers in continual evaluation of the evolving product during the product concept stage helps identify potential design improvement opportunities (Campbell & Cooper, 1999). As a firm capitalizes on customer involvement, CAD is expected to enrich the interactions between product development teams and customers. CAD is used to quickly incorporate design changes and display the "new" design as realistically (3D CAD models and coupled with virtual reality testing capabilities) as possible.

Therefore, it is hypothesized that:

Hypothesis 2: The firm's level of *Product Development Practices* has a positive effect on its level of *CAD USAGE*.

2.2.3 Operational Impact of CAD USAGE

Numerous benefits of using CAD have been alluded to in the research, often as practitioner success stories (Adler & Helleloid, 1987; Crombez, 1988; Eade, 1988; Adler, 1989; Badham, 1989; DeMatthew, 1989; Krouse et al., 1989;

Stewart, 1989; Krouse, Mills, Beckert & Drovak, 1990; Mills, 1990 & 1995; Velocci & Childs, 1990; Omanoff, 1991; Woolsey, 1991; Beatty, 1992; Puttre, 1993; Robinson, 1993; Dring, 1994; Welbourn, 1994; Hughes, 1994; Kempfer, 1994; Halliday, 1996; Tarasewich, 1996; Faries, 1997; Gould, 1997; Tan, 1998 & 1999; Weldon, 1999). These benefits include: higher engineering productivity not limited to compensating for a shortage of engineers or expensive engineering staff, improved design quality due to accurate model building, reduced mistakes in automated routine operations and standardized designs, ease of revising models leading to shorter design cycle time, increased use of common tooling and parts effectively reducing cost and order-to-delivery lead time, and enhanced data sharing, especially in terms of seamless connections to various applications (e.g., CAM, CAE, CAPP, and product development management systems) within and beyond the boundaries of the firm.

In this study, these benefits are incorporated into two performance measures: manufacturing effectiveness, and product development process performance. This distinction in performance measures is consistent with Harmsen, Grunert and Bove's (2000) finding. They surveyed top managers from 513 Danish production companies and found the top four areas of competence critical for overall firm success to be sales, market responsiveness, production management, and product development. They also concluded that product development is a central competence influenced by, as well as influencing, many other competencies.

2.2.3.1 Manufacturing Effectiveness

Literature on lean manufacturing (Suri, 1998) and JIT production system (Nelson, Mayo & Moody, 1998) suggest successful production management hinges on the responsive capabilities attained through the abilities to do quick changeovers, the production of high quality intermediate output by maintaining high quality input materials throughout the transformation processes, and the elimination of waste. The credence of "having the right materials in the right quantity (and quality) at the right place on time" requires having the right information in the right form to be available/accessible to the right people in a timely manner.

As a contributor to the product development process, a manufacturing representative can ensure the communication of manufacturability concerns to the product development team during the evolution of product design, as well as the dissemination of relevant information to production planning in a manner timely for meeting the target product launch date. As the product development process progresses toward its final stages, specific information such as product specification, estimated quantity of production, and estimated product life must lead the actual production. These information are critical to the production planning of the product -- suppliers need to be selected, production capacity needs to be assessed, master production schedules generated, supporting resources identified and scheduled, and packaging and transportation options prepared.

The scale for manufacturing effectiveness is adopted from Tracey and Vonderembse (2000).

Manufacturing effectiveness is defined as the manufacturer's ability to meet customer demand for products and services at a reasonable cost (e.g., keeping rework, material handling and production costs low, increasing outgoing product quality, reducing WIP, meeting delivery deadlines).

2.2.3.2 Product Development Process Performance

The basic tenet that product development process is a team effort necessitates measuring the outcome of the product development process in the context of teamwork. The activities and dynamics in teamwork such as shared learning, complex problem resolutions, pre-planning, and taking a systems perspective are geared toward specific goals. As a project, the product development process is constrained in terms of cost, schedule, and performance. Hence, the ability of a product development team to meet the product development project schedule in an efficient manner is a desirable outcome of any product development process.

The product development process performance measure consists of two scales: Team Process Outcome and Team Efficiency (adapted from Hong's (2000) time-to-market and development productivity). **Team Process Outcome** is defined as the team's ability to meet the time-to-market schedule (i.e., the product development time required from concept generation to market introduction).

Team Efficiency is defined as the team's ability to productively use resources in developing new products from product concept to manufacturing (e.g., allocation of resources, usage of engineering man-hours).

2.2.3.3 Research Hypotheses 3a and 3b

CAD provides a foundation for building closer linkages between the engineering and manufacturing functions. Higher level of integration with CAM means more efficient level of CAD usage (Adler & Helleloid, 1987, Badham, 1989). This translates into the ability for quicker (and frequent) data transfer from design to manufacturing. From CAD geometry, inspection programs, measuring programs, and tolerancing information can be generated for the purpose of quality assurance during production (Innala & Torvinen, 1995). Correct dimensioning and tolerancing in CAD design can result in fewer engineering change orders generated on the production shop floor. Therefore, it is hypothesized that:

Hypothesis 3a: The firm's level of *CAD USAGE* has a positive effect on its level of *Manufacturing Effectiveness*.

CAD has a minimal impact on improving the product development process if it is used purely as an electronic drafting board (Robertson & Allen, 1992; Liker et al., 1995). On the other hand, if CAD is utilized as an engineering support tool and a communication tool, its impact includes improved efficiency, enhanced coordination, and increased creativity (Baba & Nobeoka, 1998; Kappel & Rubenstein, 1999). Therefore, it is hypothesized that:

Hypothesis 3b: The firm's level of *CAD USAGE* has a positive effect on its level of *Product Development Process Performance.*

2.2.3.4 Research Hypotheses 4a, 4b, and 4c.

Product development practices affect firm performance in several ways. Koufterous, Vonderembse and Doll (2001) conclude that concurrent engineering practices significantly improve a firm's product innovation, quality, and premium pricing capabilities. Campbell and Cooper (1999) argue that customer involvement in the development of products improves a new product's advantage and the quality of the product development process. Tracey and Vonderembse (2000) found that a firm's manufacturing performance is significantly linked to its supplier's performance. Consequently, tapping into suppliers' knowledge in the product development process improves manufacturability of products (Briton, 1996; Karlsson & Ahlstrom, 1996), improves communication between engineering and procurement (Chamberlain, 1998), reduces the time to market (Karlsson & Ahlstrom, 1996) and enhances competitiveness (McGinnis & Vallopra, 1999; Tarasewich, 1996).

Therefore, it is hypothesized that:

Hypothesis 4a: The firm's level of *Product Development Practices* has a positive effect on its level of *Manufacturing Effectiveness.*

Hypothesis 4b: The firm's level of *Product Development Practices* has a positive effect on its level of *Product Development Process Performance.*

Although product and process designs affect and are affected by downstream manufacturability, the shift in the focus of excellence as the primary source of competitive advantage -- from manufacturing to product development -- provides an evolutionary rationale for historical improvements in manufacturing effectiveness as precursor to future avenues for improvements. Suri's (1998) quick response manufacturing concept emphasizes the importance for manufacturers, competing in a time-based environment, to extent their lead time reductions beyond the internal boundaries of the firm and seek reductions in external lead times as well. Kato's (1993) discussion on target costing system emphasizes the need to expand the focus of value-added activities as targets for continuous improvements to one that also encompasses non-value-added activities. Reductions in internal lead times and improvements in value-added activities are goals consistent with the just-in-time production philosophy.

Therefore, it is hypothesized that:

Hypothesis 4c: The firm's level of *Manufacturing Effectiveness* has a positive effect on its level of *Product Development Process Performance*.

2.2.4 Overall Firm Performance

Firms gain competitive advantage only when the immediate beneficial impact of CAD (product development process performance and manufacturing performance) translates into tangible firm benefits (Gupta, Prinzinger & Messerschmidt, 1998). Tu's (1999) value to customer measurement scale, which was adapted from Tracey's (1996) capability to satisfy the customer scale, encompasses the concept of manufacturing flexibility for responsiveness to customer needs (Youssef, 1993) or market responsiveness (Harmsen et al., 2000). It is selected as a measure of overall firm benefits.

Value to Customer is defined as the extent to which customers perceive a firm's product as having high value and their degree of satisfaction with the product.

2.2.4.1 Research Hypotheses 5a and 5b

Tu (1999) finds mass customization capabilities lead to better value-to-customer. Hong (2000) finds product development processes and product outcomes to be significantly and positively related to market performance. Tracey (1998) finds firm's capability to satisfy customers (in terms of price, quality, variety, fill rate, cycle time, order information, and delivery frequency) significantly affects its financial and market performance. Consequently, it is hypothesized that:

Hypothesis 5a: The firm's level of *Manufacturing Effectiveness* has a positive effect on its level of *Value to Customer (Overall Firm Performance)*.

Hypothesis 5b: The firm's level of *Product Development Process Performance* has a positive effect on its level of *Value to Customer (Overall Firm Performance)*.

The research design and methodology employed to test these hypotheses are discussed in the next chapter.

Chapter 3. Research Methods

3.1 Target Population and Research Design

The target population for this study was selected based on two general principles. First, the characteristics of the population utilized by previous research from which the measurement scales were adopted (Koufteros,1995; Tracey, 1996;Tu, 1999; Hong, 2000, and Tan et al. , 2001) were assessed. The summary shown in Table 3.1 suggests managers of medium to large manufacturing firms from three industries (i.e., SIC = 34, 35, 37) as a possible target population.

Table 3.1: Summary target population used in previous studies where measures were adopted from.

Author (Year)	Contact Person	Firm size	Industry or SIC
Koufteros(1995) 10% n=244 N=2500	Executives (members of SME)	More than 100 employees	34: Fabricated metals (except machinery & transportation) 35: Industrial and commercial machinery 36: Electronics: Electrical equipments and components 37: Transportation Equipment
Tracey (1996) 14.5% n=474 N=3333	Various managers drawn from American Business Lists®	Manufacturing firms with 50 – 1000 employees	25: Furniture and Fixtures 34: Fabricated metals (except machinery & transportation) 35: Industrial and commercial machinery 36: Electronics: Electrical equipments and components
Tu (1999) 10.37% n=303 N-2831	Manufacturing managers listed in the national manufacturers directory published by Manufacturer's News, Inc.	Medium to large firms	25: Furniture and Fixtures 30: Rubber and Miscellaneous Plastic Products 34: Fabricated metals (except machinery & transportation) 35: Industrial and commercial machinery 36: Electronics: Electrical equipments and components 37: Transportation Equipment 38: Instruments and related products.
Hong (2000) 9.1% n=205 N=2262	Managers (members of SAE) from the Midwest: OH, IN, IL, MI, PA	Not specified	34: Fabricated metals (except machinery & transportation) 35: Industrial and commercial machinery 36: Electronics: Electrical equipments and components 37: Transportation Equipment
Tan et al.(2001) 8.0% n=406 N= 5000	Managerial subscribers in U.S. to CAE magazine	Not limited by size rather firm must have CAD	34: Fabricated metals (except machinery & transportation) 35: Industrial and commercial machinery 37: Transportation Equipment

The second principle used in determining a possible target population was based on secondary data information. A two-step process was applied. In step one, the latest statistics on drafters employed (based on the 1998 National Industry Employment Matrix which includes firms with 50 or more employees) are used to identify the five industries most likely to have CAD. Table 3.2 shows the total number of employees and the percentage of drafters by 3-digit SICs, and the industry's share of drafters. For example, Engineering and Architectural Services employed a total of 93,506 people in1998, 10.33% of them were drafters, and the total number of drafters employed within this industry accounted for 33.02% of all drafters employed in 1998. It also shows the top three employers of drafters (based on the industry's share) were non-manufacturing, and the next fourteen industries (governmental, utilities, services,

Table 3.2: Number and percentages of drafter employees in 1998 by industry

SIC Code	Industry Title	1998 Employment	% Drafters within Industry (1998)	% Drafters (1998)
871	Engineering and architectural services	93,506	10.33	33.02
738	Miscellaneous business services	12,959	0.71	4.58
736	Personnel supply services	12,352	0.38	4.36
344	Fabricated structural metal products	9,434	2.03	3.33
371	Motor vehicles and equipment	4,931	0.5	1.74
354	Metalworking machinery	4,693	1.33	1.66
353	Construction and related machinery	4,298	1.7	1.52
356	General industrial machinery	4,068	1.51	1.44
355	Special industry machinery	3,592	2.01	1.27
382	Measuring and controlling devices	3,063	1.01	1.08
373	Ship and boat building and repairing	2,777	1.67	0.98
358	Refrigeration and service machinery	2,640	1.32	0.93
359	Industrial machinery, nec	2,072	0.54	0.73
349	Miscellaneous fabricated metal products	1,572	0.59	0.56
308	Miscellaneous plastics products	1,515	0.2	0.53
393	Manufactured products, nec	1,392	0.59	0.49
384	Medical instruments and supplies	1,350	0.48	0.48

and electronic sectors are excluded) with high percentage of drafters belonged to SICs 30, 34, 35, 37 and 38.

In step two, a database query of firms in the U.S with more than 100 employees was made to verify an adequate number of firms present to comprise a target population of 500 manufacturers per industry. Based on the results shown in Table 3.3, five industries were selected (each with highest estimated average number of drafters employed per firm from within 30, 34, 35, 37, and 38 respectively). They are marked as bold rows in Table 3.3.

Table 3.3: Estimated average number of drafters per firm with more than 100 employees for SIC 30, 34, 35, 37 & 38

SIC Code	Industry Group	% Workers within Industry (1998)	Number of Manufacturers (> 100 employee) within SIC	Number of Employees within SIC	Estimated average number of Drafters per manufacturer
373	Ship and boat building and repairing	1.67	273	128,970	7.89
376	Guided missiles, space vehicles, and parts	0.47	72	94,734	6.18
381	Search and navigation equipment	0.72	133	103,691	5.61
353	**Construction and related machinery**	**1.7**	**621**	**185,646**	**5.08**
355	Special industry machinery	2.01	628	157,809	5.05
351	Engines and turbines	0.66	128	93,115	4.8
358	Refrigeration and service machinery	1.32	452	163,654	4.78
344	**Fabricated structural metal products**	**2.03**	**1,340**	**292,131**	**4.43**
356	General industrial machinery	1.51	874	228,095	3.94
352	Farm and garden machinery	1	260	88,458	3.4
354	Metalworking machinery	1.33	735	172,447	3.12
382	**Measuring and controlling devices**	**1.01**	**733**	**212,246**	**2.92**
371	**Motor vehicles and equipment**	**0.5**	**1,714**	**884,720**	**2.58**
343	Plumbing and heating, except electric	0.58	158	50,011	1.84
302	Rubber products, plastic hose and footwear	0.29	19	11,598	1.77
357	Computer and office equipment	0.25	502	337,243	1.68
384	Medical instruments and supplies	0.48	737	246,824	1.61
349	Miscellaneous fabricated metal products	0.59	1,147	262,311	1.35
348	Ordnance and accessories, nec	0.25	66	35,251	1.34
342	Cutlery, handtools, and hardware	0.46	307	86,996	1.3
359	Industrial machinery, nec	0.54	729	143,765	1.06
386	Photographic equipment and supplies	0.15	89	55,085	0.93
301	Tires and inner tubes	0.09	75	73,672	0.88
346	Metal forgings and stampings	0.29	575	156,984	0.79
345	Screw machine products, bolts, etc.	0.3	272	54,615	0.6
308	**Miscellaneous plastics products**	**0.2**	**2,802**	**622,410**	**0.44**

Based on the two principles described, the target population selected for this study came from two sources: (1) respondents to a previous study that utilized a mailing list purchased from Penton Lists consisting of managerial subscribers in the U.S.A to *Computer-Aided Engineering* magazine from SICs 34, 35, and 37; and (2) a new mailing list purchased from InfoUSA consisting of 2500 (500 per SIC) medium to large manufacturers (> 100 employees) in the U.S.A from five industries (specified as 308, 344, 353, 371, and 382). Table 3.4 summarizes the entire target population used in the large-scale survey data collection.

Table 3.4: Summary of two sources of target population used

2 digit SIC	Previous respondent mailing list*	Newly purchased mailing list**	Total
30	-	456	456
34	48	582	630
35	285	564	849
37	69	337	406
38	-	327	327
Total	402	2266	2668

* Of the 406 respondents' mailing addresses from Tan et al (2001) study, four were no longer valid.
**The total number of records purchased was 2500. Each record contained up to seven 4-digit SIC per manufacturer, most frequently reported (and to break a tie, the first one reported) based on the 2-digit SIC is used as the SIC for each manufacturer. A total of 234 records were detected as replications before the first round mailing of the survey and were dropped.

Data for this empirical study was collected via a large-scale survey method. A cover letter explained the purpose of the survey and the types of questions, identified criteria for appropriate respondent, emphasized the confidentiality of each response, and requested specific information if respondent wished to receive a summary result. Each respondent in the two sources of the mailing lists (previous respondents and newly purchased) was contacted as many as four times: an introductory postcard, a survey packet, a reminder postcard, and a replacement survey packet. Appendix 1 shows the survey containing randomized scales of interest (see Appendix 2 for the exact wordings of the items by construct).

The parametrics for each scale adopted are summarized in Table 3.5. Several items were added to the CAD USAGE construct (3 items to Integrate with Customers, 1 item to Integrate with Suppliers), and the Manufacturing Effectiveness construct (2 items). For the Product Development Process Performance construct, all the items comprising the measurement scales for Time-to-Market and Development Productivity proposed by Hong (2000) were reworded, and the scales are renamed as Team Process Outcome and Team Efficiency respectively. Also, one item was added to each scale.

Table 3.5: Summary of Construct Parametrics

Construct (Total number of items)	Measurement Scale (mean, std. dev.)	Number of indicators	Construct Reliability
Product Development Practices (28 items)	Concurrent Engineering (26.87, 6.73)	8	0.92
	Customer Involvement (18.70, 3.97)	5	0.84
	Supplier Involvement (16.12, 4.97)	6	0.88
	Heavyweight Managers (18.38, 4.81)	6	0.88
	Platform Products (9.36, 2.90)	3	0.86
CAD USAGE (19 items)	Engineering Design Usage (11.25,3.51)	4	0.81
	Cross-functional Usage (15.20,4.81)	5	0.75
	Integrate w/ Customers Usage (9.78,3.53)	3 +3	0.78
	Integrate w/ Suppliers Usage (6.71,2.84)	3 +1	0.76
Product Development Process Performance (9 items)	Time-to-market * (3.52, 0.73)	5 +1	0.77
	Development Productivity** (3.46, 0.71)	4 +1	0.63
Manufacturing Effectiveness (6 items)	Manufacturing effectiveness (na)	6 +2	0.84
Overall Firm Performance (6 items)	Value-to-Customer (na)	6	0.84

* original items were revised and the construct was renamed Team Process Outcome

** original items were revised and the construct was renamed Team Efficiency

The data collected were analyzed as per Anderson and Gerbing's (1982, 1988) paradigm on testing models. They recommend a two-step process -- (1)

testing the measurement models and (2) testing the structural model -- to avoid possible interactions between the measurement and structural models.

The first step essentially involves validation of the measurement scales for all the constructs depicted in Figure 1: five product development practices, four dimensions of CAD USAGE, two product development process performances, manufacturing effectiveness, and value to customer.

All of the scales used in this study were developed as unobservable constructs with reflective indicators. That is, the observable reflective indicators are created with the perspective that they all measure the same underlying phenomenon (Fornell & Bookstein, 1982), and changes in the actual level of the phenomenon (the unobserved construct) will cause the changes in the observable indicators (Bollen, 1989; Chin, 1998). Validating each construct involved assessing via confirmatory factor analysis (CFA) the measurement model fit indices, construct (convergent and discriminant) validity, and construct reliability, as well as confirming these parametrics to be within a desirable range of values. The predictive validity of the measurement models is assessed in the second step. It involved assessing the structural model fit indices, the significance of paths, the relative importance of paths, and the significance of the effects, as well as the relative effects of the constructs. Details pertaining to the methodology and evaluation criterion for each step are presented in the sections 3.3 and 3.4 respectively.

3.2 Sample Responses, Non-response Bias and Response Bias

A total of 240 responses were received in the two rounds of survey mailings to 2668 managers from the two sources of target population. Seventeen were returned undelivered, ten indicated they do not have CAD or do product design, and eight were found to be duplicate respondents. These thirty-five were unusable. Eleven declined to participate, and nineteen are classified as incomplete because fewer than 80% of the items in two or more sections of the survey were answered. Hence, the respond rate is 7.79% ((240-35)/(2668-35)) and the effective respond rate is 6.65% ((240-35-30)/(2668-35)).

A non-response bias analysis consisted of general characteristic (industry and firm size extracted from the mailing list database) comparisons between those that responded (observed frequencies) and the population (expected frequencies) using simple chi-square (χ^2) tests. Statistical insignificance across all categories of industry and firm size confirms that the samples are representative of the target population. The result of the simple chi-square tests, shown in Table 3.6, supports that each sample is representative of its target population.

Table 3.6: Result of Non-response Bias Analysis

Criteria	Previous respondent mailing list	Newly purchased mailing list	Statistical Conclusion
SIC	$\chi^2 = 1.995$, d.f =2 Critical $\chi^2_{.05} = 5.99$	$\chi^2 = 9.033$, d.f =4 Critical $\chi^2_{.05} = 9.49$	Do not reject H_0. Each sample is representative of its population
Firm Size	$\chi^2 = 1.950$, d.f =5 Critical $\chi^2_{.05} = 11.07$	$\chi^2 = 9.447$, d.f =4 Critical $\chi^2_{.05} = 9.49$	Do not reject H_0. Each sample is representative of its population

A response bias analysis was performed as per Armstrong and Overton's (1977) recommendation, whereby the responses of the early wave were compared against those of the late wave. The responses of the first 25% of those responding from both populations (constituting a sample of 53) were compared to the last 25% of those responding (constituted a sample of 49). Simple chi-square (χ^2) tests on the general characteristics were inappropriate because for each general characteristic (industry, firm size, knowledge of respondent) there were cells with fewer than 5 observations.

T-tests show no significant difference between the early respondents and the late respondents in terms of their achievements along each of the five product development goals (reduction in product development time, design quality, product cost, manufacturing cost, and improvement in development productivity). T-tests on various items of the measurement scales demonstrated the early respondents statistically scored four items higher than the late respondents -- PP1 (an indicator of Platform Product Practice), TP1 and TP4 (indicators of Team Process Outcome), and MP6 (an indicator of Manufacturing Effectiveness). The frequency distributions of each of the four indicators show five of the late respondents did not have product platform practice, more of the early respondents indicated improvement in meeting their product development schedules, and more of the late respondents indicated no change to their manufacturing process flow. These differences suggest that the early respondents perceive their firm performance more positively than late respondents. Therefore, it was concluded that the response bias in the sample is not serious.

3.3 Measurement Model Testing Methodology

The measurement models for each construct were assessed using confirmatory factor analysis (CFA) employing LISREL for Windows version 8.12a. The typical procedure involves: (1) developing an *a priori* model based on previous studies and hypothesized relationships between observed indicators and unobserved constructs; (2) fitting the model to sample data; (3) evaluating the model in terms of goodness-of-fit and parameter estimates; and (4) re-specifying the model to improve its fit to the data (Segars, 1994).

Each hypothesized measurement model is evaluated using multiple goodness-of-fit criteria (as recommended by Wheaton (1987); Breckler (1990); Bollen & Long (1993); Tanaka (1993)). The goodness-of-fit criteria, the acceptable value(s) used, and corresponding interpretation (Hair, Anderson, Tatham & Black, 1995; Chau, 1997; Garver & Mentzer, 1999) are:

(a) Good model-fit indices (i.e., RMSEA ≤ 0.08, RMR ≤ 0.10, NNFI ≥ 0.90 and CFI ≥ 0.90) indicate the data fits the hypothesized model.

(b) Significant and high factor loadings (t-value ≥ 1.96 and completely standardized solution ≥ 0.70) show indicators effectively explain the variability of the construct.

(c) Low error terms correlation (as evident from modification index (MI) < 5) minimizes the common variance explained by the indicators.

(d) The assumption of unidimensionality is tested using the SPSSX factor analysis procedure with principle component extraction and oblimin rotation.

(e) Acceptable values for construct reliability are based on the computed construct reliability (≥ 0.70) and variance extracted (≥ 0.50).

The values for criterion (a), (b), and (c) are generated during CFA. Poor model-fit, i.e., criteria (a) not being met, indicates possible model misspecifications. The LISREL output pertaining to standardized residuals (> |2.58|), modification indices (> 5.0) and completely standardized expected change are used to guide elimination of one item at a time. Each step in the elimination process focuses on minimizing cross loadings in the model. Modification (re-specify a model or eliminate a poor indicator from a model) to a hypothesized model is made one step at a time because a single change in a model may affect other parts of the model (Segars & Grover, 1993; Garver & Mentzer, 1999).

A statistically significant item that has a low factor loading and large cross loading values (as indicated by the modification indices of lambda X and completely standardized expected change) is a likely candidate for elimination. In addition, the criterion (d) is assessed using exploratory factor analysis as a further check employing SPSSX 8.0 for Windows. The SPSSX output may provide additional insights into problematic indicators by supplementing the LISREL output.

Each modified model is re-assessed using both the CFA and SPSSX output. Iterative assessment of each modification continues until most, if not all, of the acceptable values are achieved, and the "best" measurement model is found. This search for the "best" measurement model essentially confirms and improves the convergent validity of the model. It also simultaneously assesses unidimensionality, construct validity of each measurement scale, and discriminant validity between the various scales of each construct (Segars, 1997).

After the "best" measurement models are identified, assessment of discriminant validity using the procedure recommended by Segars and Grover (1993 & 1998) are performed across constructs. Pairs of the "best " measurement scales are specified as the "fixed" model, and then the "freed" model, and their corresponding chi-square values (denoted as χ^2_{fixed} and χ^2_{freed}) are used to determine if the measurement scales have discriminant validity. The "fixed" model specification means both measurement scales are measuring the same phenomenon, as oppose to a "freed" model specification in which the pair of measurement scales are not. The critical value for the difference in chi-square ($\chi^2_{difference} = \chi^2_{fixed} - \chi^2_{freed}$) at $\alpha = 0.05$ and with 1 degree of freedom is 3.84. A significant $\chi^2_{difference}$ (a value greater than 3.84) implies that the "freed" model is an improved model as compared to the "fixed" model. In other words, the pair of measurement scales is distinctly different from one another, i.e., they have discriminant validity.

Extending this assessment over all possible combinations of pairs, all measurement scales are distinctive from one another when all possible pairs have significant $\chi^2_{difference}$ values. When multiple pairs of measurement models are assessed, statistical conclusions regarding the significant difference between all scales are made at an overall family alpha level (α_0) of 0.05. For *x* number of simultaneous pairs, the individual alpha level (α_{ind}) is computed using the formula $\alpha_0 = 1 - (1 - \alpha_{ind})^x$ and correspondingly, the critical value for the difference in chi-square ($\chi^2_{difference}$) for each pair with 1 degree of freedom depends on the α_{ind} value. If some pairs do not have significant $\chi^2_{difference}$ values, the indicators of these indiscriminating measurement scales will be assessed from the theoretical perspective for plausible reconceptualization(s).

After the discriminant validity of all constructs has been confirmed, criterion (e) can be assessed, i.e., the construct reliability and variance extracted for each construct are computed as per Hair et al. (1995).

3.4 Structural Model Testing Methodology

After confirming all measurement scales, two reasons may necessitate some of the constructs be represented as composite scores of the items retained. First, in exploratory SEM testing it was prudent to initially test for the presence of general relationships because CAD Usage is a multidimensional construct and specific relationships from the various product development practices to each dimension of CAD usage as well as from the four dimensions of CAD Usage to the three facets of performance had yet to be established.

Second, the measurement models retained posed several restrictions. Churchill (1979) contends that each latent variable should be measured by at least two indicators. Therefore a single indicator scale will be problematic. In addition, to fully capture all facets of a multidimensional or non-unidimensional construct (e.g., CAD Usage and Product Development Process Performance) requires modeling them as second-order constructs. This may cause underidentification problem, i.e., insufficient number of observed covariances to solve all the structural coefficients in the model (Mueller, 1993).

The model submitted to the structural equation model testing is shown in Figure 2. Multiple goodness-of-fit criteria were used to assess the model. The goodness-of-fit criteria, the acceptable values, and corresponding interpretation (Segars & Grover, 1993; Hair et al., 1995; Chau, 1997) are:

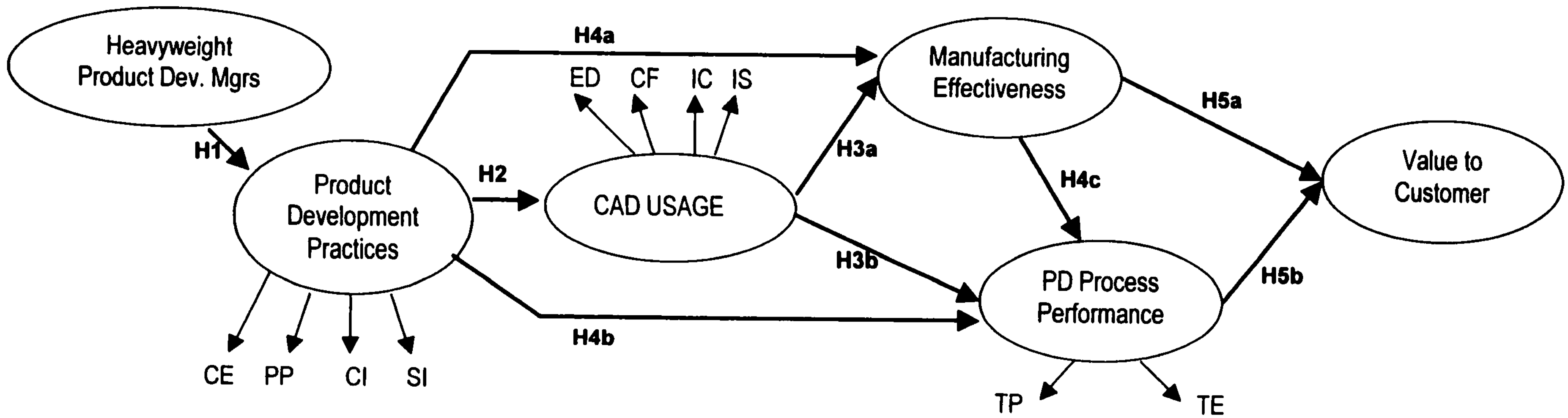
(a) Good model-fit indices (i.e., RMSEA $\leq$ 0.08, RMR $\leq$ 0.10, NNFI $\geq$ 0.90, CFI $\geq$ 0.90) indicate there is an overall fit, comparative fit to base model, and model parsimony.

(b) Significant path coefficients (t-value $\geq$ 1.96) support the hypothesized relationships between the constructs.

(c) Significant total effects (t-value $\geq$ 1.96) indicate meaningful contribution of a construct within the context of the model.

Structural equation modeling (SEM) can be utilized simultaneously to substantiate the theory on which a model is built and/or as a data-driven exploratory instrument (Bollen, 1989). In this research it is used mainly to "confirm" theory. However, the statistics provided by LISREL could have indicated the need to consider reversing the direction of a proposed path and/or adding other paths – if a theoretical basis supported doing so – during the actual testing of the model.

Figure 2: Model submitted to SEM



Notations:
CE = Concurrent Engineering: composite score = sum (mean of each dimension) = ACE1 + ACE2 + CE3
where ACE1 = mean (ce4, ce6, ce7), ACE2 = mean (ce1, ce3), and CE3 = ce8
PP = Platform Product: composite score = mean (pp1, pp2, pp3)
CI = Customer Involvement: composite score = mean (ci1, ci3,c i5)
SI = Supplier Involvement = si4
ED = Engineering Design Usage: composite score = mean (ed2, ed3, ed4)
CF = Cross-functional Usage: composite score = mean (cf1, cf3, cf4)
IC = Integrate with Customers Usage: composite score = mean (ic2, ic3, ic4)
IS = Integrate with Suppliers Usage: composite score = mean (is1, is2, is3, is4)
TE = Team Effectiveness: composite score = mean (te1, te2, te4, te5)
TP = Team Process Outcome: composite score = mean (tp1, tp2, tp4)

The result of the measurement and structural model testing are presented in Chapter 4. Based on the SEM result of the model submitted, support for the hypothesized relationships will be interpreted. Explanations and rationale will be offered where the SEM analysis does not support specific hypotheses. The discussions of the final results and post-hoc analysis are also presented in Chapter 4.

Chapter 4. Results and Discussion

4.1 Results of Measurement Model Testing

The final lists of items retained for each measurement scale (product development practices, CAD Usage, and firm performance) are attached in Appendix 2 (see also Appendix 3, which summarizes the progressive step-by-step procedure and results for each measurement scale). The final results of the CFA, tables 4.1 through 4.3, show all measurement scales have acceptable model fit indices (i.e., RMSEA ≤ 0.08, NNFI ≥ 0.90 and CFI ≥ 0.90) and all indicators retained have significant loadings (t-value ≥ 1.96) with acceptable loading values (many indicators have the acceptable completely standardized solution criteria of at least 0.70, few indicators have loadings lower than 0.70 and

Table 4.1: CFA completely standardized loadings for Product Development Practices

Item label	Loading	Error	*t*-value	Construct reliability	Variance extracted
HM1	0.66	0.56	---	0.7859	0.4794
HM4	0.66	0.57	7.09		
HM5	0.69	0.53	7.36		
HM6	0.76	0.43	7.85		
CE4	0.69	0.53	---	0.7274	0.4715
CE6	0.73	0.47	7.03		
CE7	0.64	0.59	6.61		
CE1	0.79	0.37	---	0.7212	0.5646
CE3	0.70	0.50	7.08		
CE8	Single item				
PP1	0.76	0.42	---	0.8708	0.6930
PP2	0.83	0.31	10.95		
PP3	0.90	0.19	11.40		
CI1	0.83	0.31	---	0.8277	0.6159
CI3	0.75	0.44	9.74		
CI5	0.77	0.40	9.98		
SI4	Single item				

Model fit indices: χ^2=126.44, d.f.=80, CFI=0.95, NNFI=0.93, RMSEA=0.058, RMR=0.060

none of the loadings are less than 0.60). Tables 4.1, 4.2 and 4.3 also show all of the factors, dimensions, and facets of performance have acceptable construct reliability (≥ 0.70), and all but four constructs have acceptable variance extracted of 0.50. The four constructs, *heavyweight product development managers*, teamwork in *concurrent engineering*, *cross functional CAD usage*, and *manufacturing efficiency*, have slightly less than 0.50 with a smallest variance extracted value of 0.47.

Table 4.2: CFA completely standardized loadings CAD Usage

Item label	Loading	Error	*t*-value	Construct reliability	Variance extracted
ED2	0.86	0.27	----	0.7936	0.5650
ED3	0.73	0.47	8.72		
ED4	0.65	0.58	7.93		
CF1	0.73	0.47	----	0.7219	0.4657
CF3	0.71	0.50	7.26		
CF4	0.60	0.64	6.47		
IC2	0.83	0.30	----	0.8585	0.6703
IC3	0.74	0.46	10.46		
IC4	0.88	0.22	12.18		
IS1	0.72	0.49	----	0.8615	0.6111
IS2	0.69	0.53	8.49		
IS3	0.90	0.19	10.60		
IS4	0.80	0.36	9.86		

Model fit indices: χ^2=74.09, d.f.=59, CFI=0.98, NNFI=0.98, RMSEA=0.038, RMR=0.081

Table 4.3: CFA completely standardized loadings for Firm Performance

Item label	Loading	Error	*t*-value	Construct reliability	Variance extracted
TP1	0.75	0.43	----	0.8807	0.7123
TP2	0.88	0.22	11.80		
TP4	0.89	0.21	11.86		
TE1	0.84	0.29	----	0.8596	0.6072
TE2	0.67	0.55	9.46		
TE4	0.73	0.47	10.55		
TE5	0.86	0.26	13.24		
MP6	0.68	0.54	----	0.7880	0.4818
ME1	0.67	0.56	7.20		
ME2	0.71	0.49	7.58		
ME4	0.69	0.53	7.38		
VC4	0.61	0.62	----	0.8048	0.5834
VC5	0.85	0.28	7.59		
VC6	0.81	0.35	7.64		

Model fit indices: χ^2=107.05, d.f.=71, CFI=0.96, NNFI=0.95, RMSEA=0.054, RMR=0.036

Each of the three CFA results simultaneously confirmed the unidimensionality, construct validity, and discriminant validity of the constructs within each measurement scale (i.e., five product development practices, four dimensions of CAD usage, and four facets of performance). The means, standard deviations, and the number of items retained for each measurement scale are summarized in Table 4.4.

Additional assessments of discriminant validity as per Segars and Grover (1993 & 1998), also shown in Table 4.4, confirmed the discriminant validity between the constructs across the three CFA models. An individual discriminant test, over a family of 104 pairs (x = 104), at α_{ind} of 0.0005 will result in an overall family alpha level, α_0, of 0.05. The exact critical χ^2 value at 1 degree of freedom and $\alpha = 0.0005$ is unpublished. Based on the χ^2 value at $\alpha = 0.005$ of 7.88 and the χ^2 value at $\alpha = 0.05$ of 3.84, the critical χ^2 value at $\alpha = 0.0005$ is extrapolated to be 11.92. Since, from Table 4.4, the smallest $\chi^2_{difference}$ value (26.31) is greater than 11.92, it is concluded no pairs of constructs are found to be equivalent. In other words, all the factors, dimensions, and facets of performance are distinct constructs.

Based on the Product Development Practices measurement model retained (refer to Table 4.1 and Appendix 3), Supplier Involvement is a single indicator construct and Concurrent Engineering is not unidimensional. Therefore, composite scores are computed for concurrent engineering, platform products and customer involvement and are used as the Product Development Practices indicators.

Table 4.4: Results of Discriminant Validity assessment as per Segars & Grover (1993, 1998)

	HM	CE1	CE2	CE3	PP	CI	SI	ED	CF	IC	IS	TP	TE	ME	VC
Mean	3.1287	3.3381	3.758	3.59	3.3232	3.4057	2.63	3.3638	2.6171	3.019	2.2957	3.2229	3.6734	3.3819	4.0623
Standard deviation	0.8435	0.8639	0.8197	0.97	0.9804	0.964	0.94	1.0291	1.0608	1.2784	0.9612	0.8226	0.6467	0.703	0.6059
Number of items retained	4	3	2	1	3	3	1	3	3	3	4	3	4	3	3
Heavyweight PD Manager (HM)	**0.79**														
Concurrent Engineering: Team (CE1)	79.58	**0.73**													
Concurrent Engineering: Concurrent Product-Process Development (CE2)	30.55	34.77	**0.72**												
Concurrent Engineering: Early Involvement (CE3)	154.28	82.09	26.31	**na**											
Platform Product (PP)	180.31	98.22	43.43	225.05	**0.87**										
Customer Involvement (CI)	134.74	77.40	44.50	172.16	182.69	**0.83**									
Supplier Involvement (SI)	224.45	90.01	53.24	--*	234.20	179.80	**na**								
Engineering Design Usage (ED)	144.16	95.94	42.95	145.13	142.78	145.13	149.86	**0.79**							
Cross Functional Usage (CF)	97.17	100.67	51.87	101.38	97.59	106.15	99.08	54.92	**0.72**						
Integrate with Customers Usage (IC)	223.58	112.36	49.50	230.26	246.50	180.79	231.15	132.87	66.12	**0.86**					
Integrate with Suppliers Usage (IS)	225.34	109.60	51.53	372.74	245.09	185.82	330.50	148.64	88.77	217.68	**0.86**				
Team Process Outcome (TP)	214.90	100.25	51.79	250.72	257.27	261.77	256.85	146.61	103.47	254.66	265.98	**0.88**			
Team Efficiency (TE)	172.41	91.32	34.15	306.28	336.91	186.26	360.09	129.61	101.14	223.54	374.75	145.01	**0.86**		
Manufacturing Effectiveness (ME)	105.10	107.20	49.48	108.03	94.52	196.08	114.31	110.82	92.82	114.55	117.42	75.42	56.35	**0.79**	
Value to Customer (VC)	163.10	102.65	43.00	145.10	158.31	165.76	162.60	166.23	98.52	163.95	167.62	157.69	154.02	104.55	**0.80**

* χ^2 cannot be calculated when both constructs have single item each.

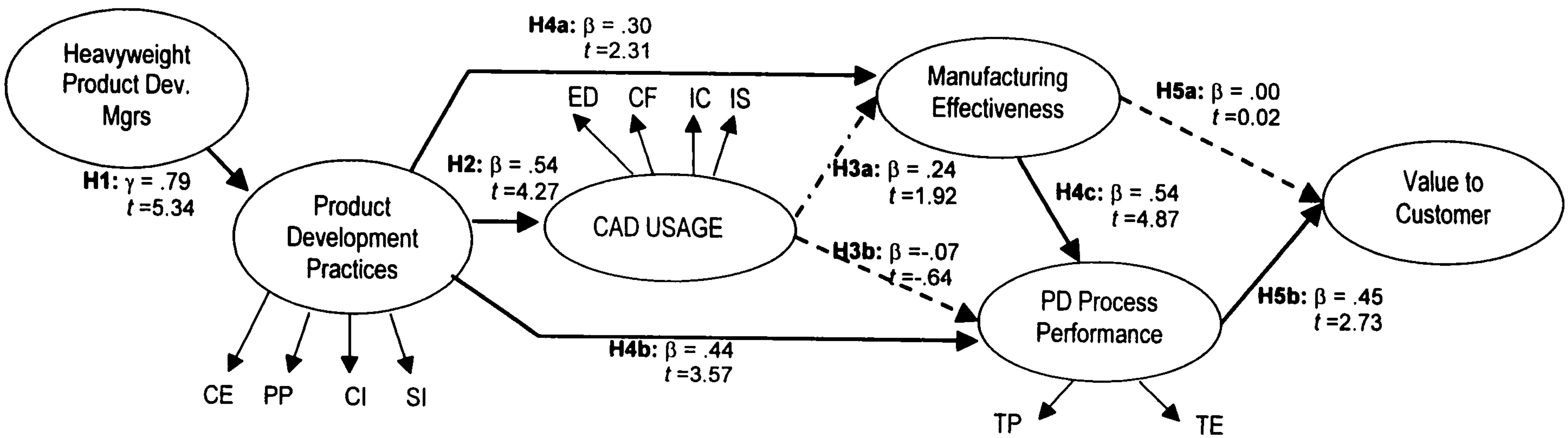
Note; critical chi-square value for α = .0005 is not published, since critical chi-square at α = .05 is 3.84 and critical chi-square at α = .005 is 7.88, the extrapolated critical chi-square at α = .0005 is 11.92 (7.88+ (7.88-3.84)).

In addition, since CAD Usage and Product Development Process Performance are multi-dimensional, these constructs are also represented using composite scores. The composite scores are computed for each of the four dimensions of CAD USAGE, and two product development process performance dimensions (team process outcome and team efficiency). The notation in Figure 2 summarizes the computation of the composite scores.

4.2 Results of Structural Equation Model Testing

The result of the structural equation model testing is shown in Figure 3. The fit indices (RMSEA = 0.051 or ≤ 0.08, RMR = 0.071 or ≤ 0.10, NNFI = 0.89 or ≈ 0.90, CFI= 0.91 or ≥ 0.90) indicated acceptable data to model fit. When the computed t-value for a path has an absolute value of greater than 1.96, the path is considered significant at $\alpha = 0.05$ within the context of the model. Figure 3 shows two insignificant paths and one marginally insignificant path. The first insignificant path is from Manufacturing Effectiveness to Value to Customer (t-value = 0.02). The second insignificant path is from CAD Usage to Product Development Process Performance (t-value = -0.64). The marginally insignificant

Figure 3: Results of SEM



Model fit indices: χ^2=260.13, d.f.=178, CFI=0.91, NNFI=0.89, RMSEA=0.051, RMR=0.071

Notations:

Signifies significant relationship in the model at $\alpha = 0.05$.

Signifies insignificant relationship in the model at $\alpha = 0.05$.

Signifies marginally insignificant relationship in the model at $\alpha = 0.05$.

path, from CAD usage to Manufacturing Effectiveness, has a t-value of 1.92 (which is slightly below the cutoff point of 1.96 at $\alpha = 0.05$).

The path coefficients (βs and γ) in Figure 3 indicate the relative strengths of the direct paths. For example, the direct path from Product Development Practices to Manufacturing Effectiveness ($\beta = 0.30$) and to Product Development Process Performance ($\beta = 0.44$) are not equal in potency. Rather, the direct effect of Product Development Practices on Manufacturing Effectiveness is roughly 70% as robust as the direct effect on Product Development Process Performance.

4.2 Evaluation of hypotheses

H1 is supported. Heavyweight Product Development Managers has a significant and positive direct effect on the firm's level of Product Development Practices (t-value =5.34 and $\gamma = 0.79$). This finding is consistent with Koufteros et al.'s (2001) contention that Heavyweight Product Development Managers are drivers of key manufacturing practices such as concurrent engineering and platform products.

H2, H4a, and H4b are supported. The firm's level of Product Development Practices has significant positive direct effects on the levels of CAD Usage, Manufacturing Effectiveness and Product Development Process Performance (t-values are 4.27, 2.31, and 3.57 with β values of 0.54, 0.30, and 0.44 respectively). Concurrent engineering practice, customer involvement and supplier involvement, through the goals of lean manufacturing and time-based competition, promote sharing of knowledge between people – within and beyond the boundary of the firm - with variant expertise and aid in building the firm's integrated knowledge. Platform products and effective utilization of CAD, on the other hand, promote systematic organization of the accumulated integrated knowledge.

H3a is marginally supported (t-value = 1.92) and H3b is unsupported (t-value = -0.64). It is plausible that the effects of CAD usage become increasingly inconsequential as firms utilize the technology over time. In other words, the attribution of the primary cause for improvements in product development process performance and manufacturing effectiveness may shift over time. Specifically, the primary cause attributed to being "enabled by CAD technology" during the initial implementation stage may have shifted to being "due to increases in human resource achievements" during the post-implementation stage as users ride the learning curve regarding the CAD technology.

H4c and H5b are supported but H5a is not. Timeliness and the ability to introduce new products or product derivatives (as measured by Product Development Process Performance) in rapid successions significantly affect a firm's quest to create Value to Customer (t-value = 2.73). Although Manufacturing Effectiveness (perceived in terms of manufacturing cost containment) has a significant positive effect on Product Development Process Performance (t-value = 4.87) but has no significant direct effect on value creation (the direct path from Manufacturing Effectiveness to Value to Customer has a t-value = 0.02).

4.3 Discussion

The total effects based on the model in Figure 3, shown in Table 4.5 are used to appraise the comprehensive impact of one construct on another within the context of the model. The t-values and the coefficients are interpreted in the same manner as the individual path t-values and the individual path coefficients (β and γ). For example, in comparing the coefficients in the far-right column of Table 4.5, one can see that of the constructs included in the model, Product Development Process Performance (total effect coefficient = 0.41) has the most influence on the Value to Customer. Heavyweight Product Development Managers (total effect coefficient = 0.21) and Manufacturing Effectiveness (total effect coefficient = 0.23) also significantly influence Value to Customer, but each exerts about half the influence of Product Development Process Performance.

Table 4.5: Direct, Indirect and Total Effects

Path or Relationship	Hypothesis	Direct Effect	Indirect Effect	Total Effects (direct + indirect)
From: Heavyweight Product Development Managers				
→ PDP	H1: +	0.79 (t = 5.34)	--	0.79 (t = 5.34)
→ CADU	None	--	0.43 (t = 4.34)	0.43 (t = 4.34)
→ ME	None	--	0.34 (t = 3.77)	0.34 (t = 3.77)
→ PDPP	None	--	0.50 (t = 4.96)	0.50 (t = 4.96)
→ VC	None	--	0.21 (t = 3.42)	0.21 (t = 3.42)
From: Product Development Practices (PDP)				
→ CADU	H2: +	0.54 (t = 4.27)	--	0.54 (t = 4.27)
→ ME	H4a: +	0.30 (t = 2.31)	0.13 (t = 1.84)	0.43 (t = 3.73)
→ PDPP	H4b: +	0.44 (t = 3.57)	0.19 (t = 2.43)	0.63 (t = 4.86)
→ VC	None	--	0.26 (t = 3.38)	0.26 (t = 3.38)
From: CAD USAGE (CADU)				
→ ME**	H3a: +	0.24 (t = 1.92)	--	0.24 (t = 1.92)
→ PDPP*	H3b: +	-0.07 (t = 0.64)	0.13 (t = 1.78)	0.07 (t = 0.58)
→ VC	None	--	0.03 (t = 0.52)	0.03 (t = 0.52)
From: Manufacturing Effectiveness (ME)				
→ PDPP	H4c: +	0.54 (t = 4.87)	--	0.54 (t = 4.87)
→ VC*	H5a: +	0 (t = 0.02)	0.23 (t = 2.40)	0.23 (t =2.19)
From: Product Development Process Performance (PDPP)				
→ VC	H5b: +	0.41 (t = 2.73)	--	0.41 (t = 2.73)

* insignificant paths and direct effects   **marginally insignificant path and direct effect.

In light of the inclusion of three insignificant paths at a 95% level of confidence, interpretations of comparative path strengths and total effects corresponding to the model in Figure 3 are performed with caution in the ensuing paragraphs along the research questions posed in section 1.2.

Question 1: Do product development practices drive the effective use of CAD, enhance manufacturing effectiveness, and improve product development process performance?

The data supports that product development practices positively affect effective use of CAD, enhance manufacturing effectiveness, and improve product development process performance. In addition, although the path from CAD Usage to Manufacturing Effectiveness is not statistically significant at 95% level of confidence, its inclusion enhances the total effect of Product Development Practices on Manufacturing Effectiveness (the indirect effect via CAD Usage contributed a value of 0.13). In a similar manner, the inclusion of the path from CAD Usage to Manufacturing Effectiveness also enhances the total effect of Product Development Practices on Product Development Process Performance (since the total effect was significant at 0.63, and the direct effect was significant at 0.44, a significant amount of indirect effect via CAD Usage contributed a value of 0.19).

These enhancements in total effects suggest CAD is beneficial to these relationships, but firms may not be leveraging or are having little success in leveraging their CAD technology in the product development process. Tyre and Orkilowski (1993) found firms rarely perform adaptations to an adopted technology beyond the first 3-year window of implementation. In this sample data, all but three firms have had CAD for 3 years or more. The average firm experience is 12.08 years.

Question 2: Does effective use of CAD increase manufacturing effectiveness and product development process performance?

The total effects of CAD Usage on Product Development Process Performance are positive but insignificant at 95% level of confidence (t-values = 0.58). In contrast, the total effect of CAD Usage on Manufacturing Effectiveness (0.24) is marginally insignificant at 95% level of confidence (t-value=1.92). There are two plausible explanations for these results.

Based on the shifts in attribution explanation, when firms compete in the arena of shrinking product life cycles and their product developments hinge on the creativity of the people involved in product design stage, the use the CAD technology may be a way to level the "playing field," i.e., it becomes a necessity (Lee, 1989). In contrast, the link from product design to manufacturing production remains a salient part of the product development process. Hence, perceptions of the effects on timeliness and efficiency in product development, in comparison to the effects on manufacturing effectiveness, are likely to diminish more rapidly as competency in using CAD increases over time.

Alternately, Adler and Helloloid (1987), Adler (1989) and Frohlich and Dixon (1999) contend the technical and non-technical adaptations to increase the integration of technologies needs to be carefully sequenced into the organization, and do not occur at the same time. It may be that many firms have been and are focusing on the non-technical (i.e., human resource and operational structures) adaptations via product development practices and are not giving equal attention to the technical adaptations (i.e., seamless integration, hardware/software and infrastructure upgrades).

Question 3: How does manufacturing effectiveness and product development process performance relate to overall performance in terms of value to the customer?

The direct effect from Manufacturing Effectiveness to Value to Customer was found to be insignificant at 95% level of confidence. The total effect (from Table 4.1) indicates that Manufacturing Effectiveness does contribute indirectly and significantly to Value to Customer (t-value = 2.19 and total effect coefficient = 0.23) through Product Development Process Performance. The direct effect from Manufacturing Effectiveness to Product Development Process Performance is significant and positive (t-value = 4.87, and $\beta = 0.54$) and the direct effect from Product Development Process Performance to Value to Customer is also significant and positive (t-value = 2.73, and $\beta = 0.41$).

These results suggest that excellence in manufacturing is a necessary prerequisite, but by itself is insufficient for value creation. Sophisticated consumers' evolving and ever increasing desires for new, innovative, and improved products mean competing manufacturers must pay close attention to the timing of product introductions, must have successively improved product development plans, and must manage several product ideas during each development iteration (Wheelwright & Clark, 1992). Also, firms need to cultivate spanning processes such that changes in the external environment are quickly captured and adjustments can be made to realign themselves in response to new information (Day, 1994).

4.4 Post-Hoc Analysis

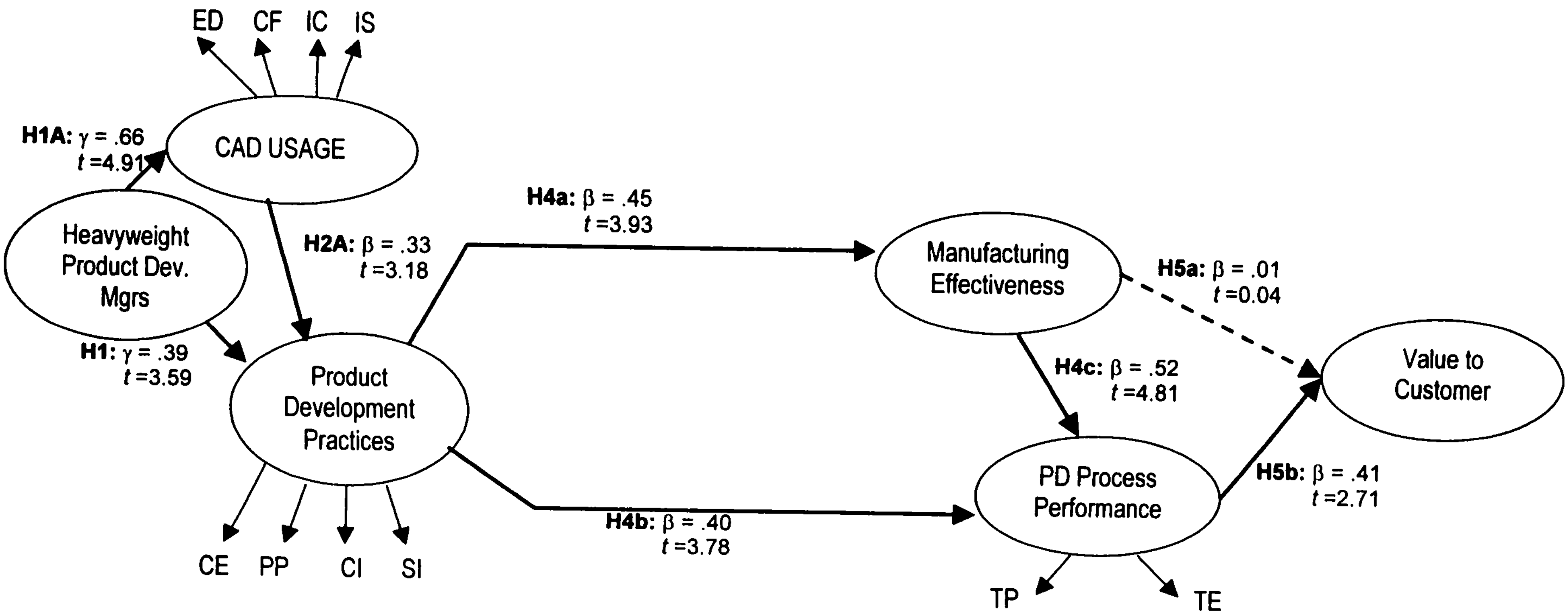
The insignificant paths regarding CAD Usage to Manufacturing Effectiveness and CAD Usage to Product Development Process Performance suggest that an alternate model may better fit the data. It is plausible that a firm's utilization of CAD technology is greatly influenced by how top management views the adoption of CAD. Lee (1989) proposed a firm's adoption of CAD technology as either "market-driven" (management viewed the adoption of CAD as a competitive necessity) or "technology-driven" (management viewed the adoption of CAD as a competitive opportunity).

CAD utilization as proposed in Figure 2, reflects its influence as more consistent with a market-driven adoption. That is, firms adopt CAD technology as a reaction to the competitive pressures in the marketplace. How CAD is utilized is dictated by the existing product development practices. Top management typically make these decisions with little input from the end-users.

An alternate model that reflects an influence more consistent with a technology-driven adoption of CAD is shown in Figure 4. A firm's adoption of CAD technology is driven by the recognition of potential benefits, typically through end-user involvement, and these recognized benefits influence how it will be used.

Input from, and acceptance by end users has been identified as critical to successful implementation of technology (Leonard-Barton, 1988; Leonard-Barton & Deschamp, 1988). An important consideration when involving end-users in the CAD implementation decisions is their level of technical competency, i.e., their pre-existing computer skills (Adler & Helloloid, 1988). On the one hand, as the available pool of labor force becomes increasingly computer literate, it becomes more likely firms can operate under a technology-driven mode and be able to extract full use of the technology within a three-year window (Tyre & Orkilowski, 1993). On the other hand, sentiments consistent with "resistance to change" may require some adaptations to be implemented in a form of management mandates (Robertson & Allen, 1992) in order to elevate the communication value of CAD (Baba & Nobeoka, 1998; Robertson & Allen, 1993). Hence, heavyweight product development managers are likely to promote effective utilization of technology along with time-based product development practices, and the firm's product development practices are more likely to support beneficial technology-enabled processes (these relationships are depicted in Figure 4 as H1A and H2A).

Figure 4: Alternate Research Model & SEM Results



Model fit indices: χ^2=263.30, d.f.=179, CFI=0.90, NNFI=0.89, RMSEA=0.052, RMR=0.072

Notations:

⟶ Signifies significant relationship in the model at α = 0.05.

- - ▶ Signifies insignificant relationship in the model at α = 0.05.

The alternate research model is similar to the proposed research model in that it supports CAD utilization as a precursor to its impact on the firm. However, it is different from the proposed model in that the effects of CAD utilization on Manufacturing Effectiveness, Product Development Process Performance and Value to Customer are not direct, rather they are indirect via product development practices. The result of testing the structural equation model for the alternate model (see Figure 4) demonstrates the fit indices are as good as the proposed research model, and the path from Manufacturing Effectiveness to Value to Customer (t-value = 0.04) remains insignificant.

The positive and significant direct path from Heavyweight Product Development Managers to CAD Usage (at 95% confidence level, γ = 0.66 and t-value = 4.91) is consistent with Leonard-Barton and Deschamp's (1988) contention that perceived management commitment and support (e.g., through mandates on how the CAD technology is to be utilized) have positive influence on the effectiveness of highly motivated end-users. Furthermore, the relative strength of the direct effects, of Heavyweight Product Development Managers, on CAD Usage (γ = 0.66) is approximately twice the potency than on Product Development Practices (γ = 0.39). Also, the direct path from CAD Usage to Product Development Practices is positive and significant (β = 0.33 and t-value = 3.18).

The detailed effects (direct, indirect, and total) corresponding to the alternate model (depicted in Figure 4 and shown in Table 4.6) support the indirect impact of effective CAD utilization on firm performance. Specifically, the effects indicate: (a) CAD USAGE positively enhance the effects of Heavyweight Product Development Managers on Product Development Practices (i.e., significant indirect effect coefficient = 0.13), (b) Product Development Process Performance being the most influential construct regarding Value to Customer (total effect coefficient = 0.41), and (c) Product Development Process Performance is influenced most by Product Development Practices (total effect coefficient =0.64).

Table 4.6: Post-Hoc Analysis's Direct, Indirect and Total Effects

Path or Relationship	Hypothesis	Direct Effect	Indirect Effect	Total Effects
From: Heavyweight Product Development Managers				
→ PDP	H1: +	0.66 (t = 4.91)	0.13 (t = 2.70)	0.79 (t = 5.36)
→ CADU	**H1A	0.39 (t = 3.59)	--	0.39 (t = 3.59)
→ ME	None	--	0.36 (t = 3.98)	0.36 (t = 3.98)
→ PDPP	None	--	0.50 (t = 5.02)	0.50 (t = 5.02)
→ VC	None	--	0.21 (t = 3.45)	0.21 (t = 3.45)
From: Product Development Practices (PDP)				
→ CADU	**H2-deleted	--	--	--
→ ME	H4a: +	0.45 (t = 3.93)	--	0.45 (t = 3.93)
→ PDPP	H4b: +	0.40 (t = 3.78)	0.24 (t = 3.40)	0.64 (t = 4.92)
→ VC	None	--	0.26 (t = 3.42)	0.26 (t = 3.42)
From: CAD USAGE (CADU)				
→ PDP	**H2A	0.33 (t = 3.48)	--	0.33 (t = 3.48)
→ ME	**H3a-deleted	--	0.15 (t = 2.80)	0.15 (t = 2.80)
→ PDPP	**H3b-deleted	--	0.21 (t = 3.10)	0.21 (t = 3.10)
→ VC	None	--	0.09 (t = 2.60)	0.09 (t = 2.60)
From: Manufacturing Effectiveness (ME)				
→ PDPP	H4c: +	0.52 (t = 4.81)	--	0.52 (t = 4.81)
→ VC*	H5a: +	0.01(t = 0.04)	0.21 (t = 2.38)	0.22 (t = 2.10)
From: Product Development Process Performance (PDPP)				
→ VC	H5b: +	0.41 (t = 2.71)	--	0.41 (t = 2.71)

* insignificant path and direct effects.

** paths added/deleted relative to final model reported.

These results suggest that the recognized potential benefits, likely identified with the input from end-users', are a plausible determinant of how the technology will to be used. Management may need to emphasize its desire to fully realize the potential of CAD technology through mandates in how the technology is utilized, progressively increasing its technology-enabled processes, and subsequently reshaping the firm's product development practices.

In Chapter 5, the practical and theoretical implications of the measurement scales and the findings regarding the hypothesized relationships, the limitations of this research, preliminary assessments of contextual variables, and possible directions of future research are presented.

Chapter 5. Implication, Limitation, and Future Research

5.1 Implication

From the theoretical perspective, the measurement scales adapted for this research are validated in terms of content and discriminant validity and reliability. The structural equation model, which examines all the components in the model simultaneously in assessing whether the causal inferences are consistent with the actual data (Bollen, 1989), supports the ability of the model to predict the data. Table 5.1 summarizes (in terms of the number of indicators used and construct reliability) the comparisons for each measurement scale between its original source and the retained items in this study. In general, the construct reliabilities are comparable considering that fewer items are retained. Three measurement concerns based on the results of this study warrant future validation:

- The lack of unidimensionality in the Concurrent Engineering practice scale necessitated breaking the domain down into its three underlying components of team, concurrency, and early involvement. Koufteros's (1995) work supported a unidimensional scale of Concurrent Engineering. The data in this study supports Concurrent Engineering to be consisting of three dimensions. Further validation may resolve this discrepancy regarding the dimensionality of the Concurrent Engineering construct.

Table 5.1: Comparison of number of items per construct and construct reliability

Construct	Measurement Scale	Number of indicators		Construct Reliability	
		Original	Retain	Original	Retain
Product Development Practices (adapted from Koufteros (1995))	Concurrent Engineering	8		0.92	
	Team		3		0.73
	Concurrent Product-Process Development		2		0.72
	Early Involvement		1		na
	Customer Involvement	5	3	0.84	0.83
	Supplier Involvement	6	1	0.88	na
	Heavyweight Managers	6	4	0.88	0.79
	Platform Products	3	3	0.86	0.87
CAD USAGE (adapted from Tan et al. (2001))	Engineering Design Usage	4	3	0.81	0.79
	Cross-functional Usage	5	3	0.75	0.72
	Integrate w/ Customers Usage	3	3	0.78	0.86
	Integrate w/ Suppliers Usage	3	4	0.76	0.86
Product Development Process Performance (adapted from Hong (2001))	Team Process Outcome*	5	3	0.77	0.88
	Team Efficiency**	4	4	0.63	0.86
Manufacturing Effectiveness (adapted from Tracey & Vonderembse (2000))	Manufacturing Effectiveness	6	3	0.84	0.79
Overall Firm Performance (adapted from Tu(1999))	Value-to-Customer	6	3	0.84	0.80

* revised and adapted from Time-to-Market (Hong, 2000) ** revised adapted from Development Productivity (Hong, 2000)
na = construct reliability cannot be calculated for single item construct.

- A single indicator is retained for Supplier involvement practice due to inability in the original items to clearly distinguish which party has the design responsibility. A latent construct as measured by a single indicator posed a limitation on the measurement scale (the reliability of the construct cannot be assessed) as well as the rigor of model testing (full model of SEM testing cannot be performed).
- Measuring Cross Functional Usage remains a challenge. The difficulty may be that how other functions use the information they retrieved through direct access is not transparent. When limited access is given to various other functions, routine generation of standard reports and special reports

generated upon request are typically used to disseminate relevant information. The availability of good information through standard reports can diminish the need for special reports. Although the type of information generated is transparent, whether or not and how others used it is not. Several considerations that should be taken into account to better operationalize this dimension include access differential (direct versus indirect), the functions (Sales/Marketing, Purchasing, Product Planning, Manufacturing and Quality Control), and information format (referential versus operational needs, e.g., material and parts specification for a product, material or components supplier information versus tooling requirements, CNC programs, critical dimensions of components).

The proposed structural equation model confirms the value of product development practices in utilizing CAD effectively, advancing toward lean manufacturing, meeting product introduction deadlines, and improving productivity in product development. Although effective use of CAD was not detected as having a significant direct impact on either manufacturing effectiveness or product development process performance at a 95% level of confidence, effective utilization of CAD did enhance the firms' levels of manufacturing effectiveness, product development process performance, and value to customer.

The alternate structural equation model suggests a firm that utilized CAD effectively positively enhanced its product development practices, which in turn helped the firm in advancing toward lean manufacturing, meeting product introduction deadlines, improving productivity in product development, and ultimately creating greater value to customers.

From the practical standpoint, the retained measurement scales form a short forty-three questions survey that can be used to create a benchmark measure of a firm's level of product development practices, CAD Usage, and performance. Average scores can be computed from the responses to the survey, comprised of the items retained listed by measurement scale in Appendix 2, and be compared to the sample benchmark (average scores generated from the sample in this study, previously summarized in Table 4.4) shown in Table 5.2. Specific scores below the sample benchmark identify areas for improvement. In addition, periodic use of the survey will allow a firm to chart and monitor any change over time.

Table 5.2: Sample Mean and Standard Deviation for each measurement scale

Measurement Scale	Mean	Standard Deviation
Concurrent Engineering		
Team	3.34	0.86
Concurrent Product-Process Development	3.76	0.82
Early Involvement	3.59	0.97
Customer Involvement	3.41	0.96
Supplier Involvement	2.63	0.94
Heavyweight Managers	3.13	0.84
Platform Products	3.32	0.98
Engineering Design Usage	3.36	1.03
Cross-functional Usage	2.62	1.06
Integrate w/ Customers Usage	3.02	1.28
Integrate w/ Suppliers Usage	2.30	0.96
Team Process Outcome	3.22	0.82
Team Efficiency	3.67	0.65
Manufacturing Effectiveness	3.38	0.70
Value-to-Customer	4.06	0.61

The results of the proposed model in this study also suggest an opportunity to leverage the CAD technology as a component of interwoven technologies. Firms in this study have not been very successful in doing so. It is plausible that the lack of attention to technical adaptations may be due to the inability to keep up with technical upgrades and to absorb both the technical cost and the human resource requirements. With the advent of firms specializing in IT infrastructures, there is an opportunity for firms to achieve better alignment between the technical and non-technical adaptations and to do so in some parallel manner with cost effective implications. That is, manufacturing firms can focus on the non-technical aspects of integration and outsource the technical aspects as a strategy to expedite and be more successful in leveraging integrated technologies.

Additionally, the results from the alternate model in this study suggest the degree of alignment between the firm's technical and non-technical adaptations may depend on how the firm views the role of CAD technology. When the role of CAD technology is perceived as "leveling the playing field", firms tend to apply it more as a substitute tool. In other words, improving the speed of the existing business processes and not necessarily improving the business processes. Consequently, the non-technical adaptations resulted in marginal improvements. In contrast, when the role of CAD technology is perceived as "a means to creating competitive advantage", firms tend to place greater weight on the end-users' input regarding technology-enabled opportunities, and are more flexible in adapting their practices. In other words, technical adaptations must precede the non-technical adaptations to enable significant improvements.

5.2 Limitations of this research

The sample data (n=175) used in this research were collected from managers of the U.S.A firms operating in one of five industries. The sample size limits the rigor of analysis that could be performed using SEM, i.e., the analyses are not performed to control for industry or firm size differences (see section 5.3 for the control variables analyses performed). Hence, the conclusions are based on the aggregate responses from all five industries with firm sizes that range from small to large.

A related concern is the impact of sample size on the power to detect the effect of interest. Cohen (1977) suggests studies be design to achieve alpha level of at least 0.05 with the power levels of 80 percent. A sample size of 175, at alpha of 0.05 and power level of 80%, is adequate in detecting an effect size of 0.35. In other words, a statistically supported hypothesis in this study (performed at 95% level of confidence) means the sample data detected the effect and the size is larger than 0.35. On the other hand, a statistically unsupported hypothesis in this study does not imply the non-existence of effect. Rather the effect size may be too small (less than 0.35), and the sample of 175 is not adequate to detect it.

Considering that the proposed model and the alternate model were equal in predicting the data, it is plausible that an aggregation effect is present in the testing of the structural model. In this study, further assessment to check for this aggregation effect is hindered by the small sample size.

5.3 Additional Analysis: Control Variables

Three control variables (firm size, industry and type of firm) are assessed independently in the ensuing paragraphs to provide some insight into their affects on the six constructs of interest (heavyweight product development manager, product development practices, CAD USAGE, Manufacturing Effectiveness, Product Development Process Performance, and Value to Customer) and their relationships using t-tests on means and correlation matrix.

5.3.1 Firm Size: Small, Medium, and Large

Table 5.3 shows the results of ANOVA tests on composite scores for each of the six latent constructs depicted in Figure 2 across firms based on firm size (small, medium and large). From Table 5.3, the mean ratings of heavyweight

Table 5.3: Comparison of means by firm size

Constructs	All firms		Small (<100)		Medium(100-499)		Large (500+)		Significance
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	(p-value)
Heavyweight Product Managers (HM)	3.1287	0.8435	3.1111	0.9171	2.9685	0.8745	3.3989	0.6398	0.022
Product Development Practices (PDP)	19.4486	4.0755	17.5988	4.7177	19.8806	3.5943	20.8936	3.1990	0.000
CAD Usage (CADU)	11.2957	3.1365	10.7840	3.2892	11.1734	3.0160	12.0762	3.0588	0.107
Manufacturing Effectiveness (ME)	3.3819	0.7030	3.2253	0.6719	3.4628	0.6875	3.4344	0.7464	0.141
Product Development Process Performance (PDPP)	6.8752	1.3773	6.9398	1.3872	6.8142	1.4697	6.8972	1.2325	0.872
Value to Customer (VC)	4.0623	0.6059	3.9630	0.5780	4.1005	0.6253	4.1170	0.6058	0.348

Note: computations for the composite score of each construct: HM = sum(hm1, hm4, hm5, hm6); PDP=sum(CE, PP, CI, SI); CADU=sum(ED, CF, IC, IS); ME=sum(mp6, me1, me2, me4); PDPP= sum(TP, TE); VC=sum(vc4, vc5, vc6) product development managers and product development practices are not equal across the three firm sizes. Specifically, large firms have statistically higher mean ratings in heavyweight product development managers than medium firms, and statistically higher mean ratings in their product development practices than small firms.

Table 5.4: Correlation matrix stacked by firm size

	Firm size	HM	PDP	CADU	ME	PDPP	VC
	All	1.000					
HM	Small(<100)	1.000					
	Medium(100-499)	1.000					
	Large (500+)	1.000				Sample size	
	All	0.501**	1.000			175	
PDP	Small(<100)	0.513**	1.000			54	
	Medium(100-499)	0.493**	1.000			74	
	Large (500+)	0.529**	1.000			47	
	All	0.301**	0.435**	1.000			
CADU	Small(<100)	0.344*	0.565**	1.000			
	Medium(100-499)	0.227	0.294*	1.000			
	Large (500+)	0.321*	0.380**	1.000			
	All	0.219**	0.307**	0.245**	1.000		
ME	Small(<100)	0.245	0.156	0.207	1.000		
	Medium(100-499)	0.153	0.301**	0.114	1.000		
	Large (500+)	0.373**	0.459**	0.448**	1.000		
	All	0.342**	0.375**	0.264**	0.543	1.000	
PDPP	Small(<100)	0.156	0.340*	0.241	0.509**	1.000	
	Medium(100-499)	0.459**	0.588**	0.254*	0.540**	1.000	
	Large (500+)	0.328*	0.157	0.338*	0.646**	1.000	
	All	0.223**	0.371**	0.193*	0.201**	0.279**	1.000
VC	Small(<100)	0.445**	0.499**	0.305*	0.270*	0.409**	1.000
	Medium(100-499)	0.124	0.394**	0.089	0.233**	0.226	1.000
	Large (500+)	0.155	0.089	0.189	0.041	0.244	1.000

* correlation is significant at the 0.01 level ** correlation is significant at the 0.05 level

Table 5.4 depicts the correlations between the composite scores of the six constructs stacked in each cell based on all firms and by each firm size. The three patterns of correlations observed based on firm size are:

- Medium firms have the weakest correlations between CAD usage construct and four other constructs (heavyweight product development managers, product development practices, manufacturing effectiveness, and value to customer).

- All five constructs were insignificantly correlated with Value to Customer for large firms but were significantly correlated for small firms.
- Correlations between heavyweight product development managers, product development practices, and CAD usage with Manufacturing Effectiveness were significant for large firms but insignificant for small firms.

The differences in means and the patterns in correlations seem to provide some support for Meredith's (1987) contention that large firms have the strategic advantage in terms of excess resource/capacity (as opposed to small firms' strategic advantage of flexibility). The results suggest large firms have the means, financially as well as human resource-wise, to put in place formal heavyweight product development managers, concurrent engineering, platform products, customer involvement, and supplier involvement practices, and they did so more than small and medium firms.

Small firms were comparable in heavyweight product development managers to large firms. Medium firms had comparable concurrent engineering, platform products, customer involvement, and supplier involvement practices as large firms. These contrasts and the correlation pattern with CAD usage suggest heavyweight product development managers may be a better predictor of effective technology utilization than the other product development practices.

All firms, by size, were equal in their utilization of CAD. The correlations between manufacturing effectiveness and product development process performance were, also, equally strong. These suggest firms of all sizes recognized the interrelationship between R&D and Manufacturing functions and the potential integrative value of technology such as CAD. However, the manner to which each firm size succeeds differed. The primary performance focus of large firms was to achieve manufacturing excellence. For the small firms, the focus was on creating customer value. Medium firms were better at product development process performance.

5.3.2 Industry: Transportation Equipment and Fabricated Metal

For industry as a control variable, the two most sizable industries in number of respondents were compared. Tables 5.5 show the results of t-tests comparisons of composite scores for each of the six latent constructs based on the selected SIC (34 and 37). From Table 5.5, the transportation equipment industry has statistically higher mean ratings in CAD usage and manufacturing effectiveness than the fabricated metal industry.

Table 5.5: Comparison of means by selected SIC

	All firms		Fabricated Metal		Transportation		Significance
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	(p-value)
Heavyweight Product Managers (HM)	3.1287	0.8435	3.0382	0.8777	3.2609	0.8376	0.279
Product Development Practices (PDP)	19.4486	4.0755	18.8760	4.5156	20.3696	3.3295	0.142
CAD USAGE (CADU)	11.2957	3.1365	11.2355	3.2161	12.7935	3.0949	0.040
Manufacturing Effectiveness (ME)	3.3819	0.7030	3.3246	0.5957	3.6775	0.7227	0.018
Product Development Process Performance (PDPP)	6.8752	1.3773	6.8566	1.2501	7.1594	1.0883	0.292
Value to Customer (VC)	4.0623	0.6059	4.0353	0.6279	4.0870	0.5363	0.719

Note: computations for the composite score of each construct: HM = sum(hm1, hm4, hm5, hm6); PDP=sum(CE, PP, CI, SI); CADU=sum(ED, CF, IC, IS); ME=sum(mp6, me1, me2, me4); PDPP= sum(TP, TE); VC=sum(vc4, vc5, vc6)

Table 5.6 depicts the correlations between the composite scores of the six constructs stacked in each cell based on all firms and by each SIC. Three patterns of correlations were observed based on the two industries:

- In general the firms in the fabricated metal industry have the stronger correlations with heavyweight product development managers construct.
- For the fabricated industry, CAD usage was insignificantly correlated with manufacturing efficiency and product development process performance but was significantly correlated with value to customer. In contrast, CAD usage was significantly correlated with manufacturing efficiency but insignificantly correlated with product development process performance and value to customer.
- For the fabricated industry, product development process performance and value to customer were significantly correlated with product development practices. The correlations were insignificant for the transportation industry.

It is plausible that firms in the transportation industry tend to be downstream in the value-added chain to the firms in the fabricated metal industry. Firms in the fabricated metal industry have few supplier links, many customer links, and their products tend to be at the extreme of either a mass produced standardize parts or a few of the highly specialized production tools. Both operations permit limited opportunities in leveraging CAD files internally. Consequently, firms in the fabricated industry were affected more by product development leadership than effective use of CAD and the positive affects on the firm were largely in terms of product development process performance and value to customer, and insignificantly in terms of manufacturing efficiency.

In contrast the firms in transportation industry tend to be assemblers with some level of mass customization, and consequently, have more opportunities to accrue benefits from effective use of CAD and manufacturing efficiency.

Although not explored here, there may be an interaction effect of firm size by industry as well. More firms --14 of 23 -- in the transportation industry were large firms and more firms in the fabricated metal industry were not (42 were medium, 32 were small and only 10 were large).

Table 5.6: Correlation Matrix stacked by industry.

	SIC	HM	PDP	CADU	ME	PDPP	VC
HM	All	1.000					
	Fabricated metal	1.000					
	Transportation	1.000				Sample size	
PDP	All	0.501**	1.000			175	
	Fabricated metal	0.567**	1.000			86	
	Transportation	0.467*	1.000			23	
CADU	All	0.301**	0.435**	1.000			
	Fabricated metal	0.425**	0.418**	1.000			
	Transportation	0.095	0.569**	1.000			
ME	All	0.219**	0.307**	0.245**	1.000		
	Fabricated metal	0.101	0.292**	-0.030	1.000		
	Transportation	-0.044	0.434*	0.463*	1.000		
PDPP	All	0.342**	0.375**	0.264**	0.543**	1.000	
	Fabricated metal	0.344**	0.484**	0.204	0.523**	1.000	
	Transportation	0.347	0.234	0.030	0.379	1.000	
VC	All	0.223**	0.371**	0.193*	0.201**	0.279**	1.000
	Fabricated metal	0.323**	0.467**	0.240*	0.172	0.326**	1.000
	Transportation	0.048	-0.163	-0.292	-0.130	0.329	1.000

* correlation is significant at the 0.01 level ** correlation is significant at the 0.05 level

5.3.3 Type of Firm: Make-to-Order and Make-to-Stock

Table 5.7 shows the results of t-test comparisons of composite scores for each of the six latent constructs based on type of firm (make-to-order or make-to-stock). From Table 5.7, make-to-order firms have statistically higher mean ratings than make-to-stock firms on heavyweight product development managers, CAD USAGE, and product development process performance constructs.

Table 5.7: Comparison of means by type of firm

	All firms		**Make to Order***		**Make to Stock***		Significance
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	(p-value)
Heavyweight Product Managers (HM)	3.1287	0.8435	3.1789	0.8153	2.8429	0.9512	0.040
Product Development Practices (PDP)	19.4486	4.0755	19.4570	3.9355	19.1759	4.8049	0.719
CAD USAGE (CADU)	11.2957	3.1365	11.5085	3.3080	10.2153	2.5763	0.032
Manufacturing Effectiveness (ME)	3.3819	0.7030	3.4084	0.6462	3.2523	0.8641	0.239
Product Development Process Performance (PDPP)	6.8752	1.3773	7.0169	1.2883	6.4352	1.5094	0.023
Value to Customer (VC)	4.0623	0.6059	4.0538	0.5898	4.0926	0.6790	0.737

Note: computations for the composite score of each construct: HM = sum(hm1, hm4, hm5, hm6); PDP=sum(CE, PP, CI, SI); CADU=sum(ED, CF, IC, IS); ME=sum(mp6, me1, me2, me4); PDPP= sum(TP, TE); VC=sum(vc4, vc5, vc6).
*Firms reporting >50% make to order = make to order, >50% make to stock = make to stock, 50% of either make to order or stock are recoded as missing.

Table 5.8 depicts the correlations between the composite scores of the six constructs stacked in each cell based on all firms and each type of firm. Three observations regarding the pattern of correlations based on make-to-order and make-to-stock firms are:

- The correlations of product development practices and CAD usage with manufacturing efficiency were significant for make-to-order firms and insignificant for make-to-stock firms.
- The correlation of heavyweight product development managers with CAD usage was significant for make-to-order firms but was insignificant for make-to-stock firms. In contrast, the correlations of heavyweight product

development managers with manufacturing efficiency and value to customer were insignificant for make-to-order firms but were significant for make-to-stock firms.

- The correlations with product development process performance were significant for both types of firms.

Table 5.8: Correlation Matrix stacked by type of firm.

	Type	HM	PDP	CADU	ME	PDPP	VC
HM	All	1.000					
	Make to order	1.000					
	Make to stock	1.000				Sample size	
PDP	All	0.501**	1.000			175	
	Make to order	0.472**	1.000			128	
	Make to stock	0.644**	1.000			36	
CADU	All	0.301**	0.435**	1.000			
	Make to order	0.332**	0.479**	1.000			
	Make to stock	0.034	0.370*	1.000			
ME	All	0.219**	0.307**	0.245**	1.000		
	Make to order	0.118	0.372**	0.252**	1.000		
	Make to stock	0.401*	0.102	0.243	1.000		
PDPP	All	0.342**	0.375**	0.264**	0.543**	1.000	
	Make to order	0.316**	0.311**	0.228**	0.579**	1.000	
	Make to stock	0.396*	0.543**	0.394*	0.421*	1.000	
VC	All	0.223**	0.371**	0.193*	0.201**	0.279**	1.000
	Make to order	0.142	0.335**	0.218*	0.228*	0.273*	1.000
	Make to stock	0.468**	0.525**	0.213	0.247	0.374*	1.000

These findings appear to be consistent with Buxey's (1990) observation that adopters of CAD technology tend to be firms with high product variety to begin with. In other words, make-to-order firms have greater beneficial opportunities afforded through effective use of CAD than make-to-stock firms. Interestingly the significantly higher ratings on heavyweight product development managers and CAD usage among the make-to-stock firms were also significantly correlated, but the lower ratings were clearly uncorrelated. For firms with both make-to-stock and make-to-order operations, a situational strategy may be warranted. That is, as to when heavyweight product development managers should emphasize manufacturing efficiency and value creation or when they need to push for effective use of CAD. Although make-to-order firms achieved significantly greater product development process performance than make-to-stock firms, its correlations with other constructs (being consistent across both types of firm) suggest this performance construct is robust.

5.4 Future Research

This study validates many of the measurement scales adopted consequently these scales need not be revalidated in future surveys. Specifically, three scales (Concurrent Engineering and Supplier Involvement practices, and Cross Functional Usage) warrant additional validation. Hence, the focus of a future survey is to obtain a larger sample size for a more rigorous statistical analysis. In addition to cross validating the research model by firm size, industry, and type of firm (i.e., assess the robustness of the relationships), two other possible control variables to use include the level of firm's advance manufacturing technology and the amount of firm's CAD experience. A larger sample size would also allow more rigorous assessment of the proposed and the alternative models.

Based on the sample data collected, specific relationships within CAD Usage dimensions have not been fully explored in this study. A possible line of future research is to fully explore relationships among the four dimensions of

CAD USAGE in the context of a single product development practice as the antecedent and a single measure of firm performance as the outcome.

As an evolving technology, a longitudinal study of the impact of CAD will require repeated data collection from the respondent firms. A potential approach, to obtain richer data, to explore is the use of the recommended short questionnaire with direct observation method on a limited number of firms to be studied in a longitudinal manner. Also, another possible extension to this research is to expand the scope of firms surveyed to include other industries as well as other countries (i.e., do an international or a multi-countries research).

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Appendix 1: Survey

SURVEY FOR MEASURING FIRM'S UTILIZATION AND IMPACT OF COMPUTER-AIDED DESIGN SYSTEMS

General Information *Types of questions*: How CAD is used for product development, benefits derived, and factors that might influence use.
Purpose: To set benchmarks for best practices in the use of CAD for product development.
Appropriate respondent: A person who has an overall knowledge of the firm's product development practices, how CAD and related technologies are used, and is cognizant of the firm's competitive position.

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Please do not fold this survey as the pages are to be scanned.

General Instructions:

This questionnaire is part of a nationwide study to document product development practices, computer-aided design (CAD) and related technology application and their impact on creating higher value to customers. Questions regarding business-to-business (B2B) e-commerce are also included as it may have a moderating influence.

The questionnaire is divided into nine sections. Each question requires that you choose the alternative that best fits your views on that topic. It should take you approximately 25 minutes to fill out this questionnaire. No additional file search is needed to answer the questions. There are no right or wrong answers. I am interested only in your perceptions. **The information provided by you will be treated in the strictest confidence.** Your responses will be entered in a coded format and only be used for aggregated statistical analysis.

If you wish to receive a summary result of this study please enclose a business card with the completed survey.

Thank you for your cooperation. With your assistance, this study can help clarify a number of issues pertaining to the effectiveness of CAD that have only been addressed so far at a theoretical level. A business-reply envelope is enclosed for your convenience.

Please use a pencil or a ballpoint pen to fill in the bubbles. An example of filling a bubble:

(1) (2) ● (4) (5) (X)

Section 1: Technology

For each of following technologies, please rate (1) the extent of your firm's current use, (2) the types of integration with CAD, and (3) whether it is used to support CAD/CAM activities with your supplier(s) and customer(s).

	Extent of current use						Integration with CAD					Support CAD/CAM	
	Not at all	A little	Moderately	Much	A great deal	Not Applicable	Stand Alone	Island of automation	Partial Integration	Full Integration	Not Applicable	Yes	No
CAD	(1)	(2)	(3)	(4)	(5)	(X)							
CAM	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)		
CAPP	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)		
MRP / MRP II	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)		
CMM (Coordinated Measuring Machine)	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)		
NC, CNC or DNC (numerical control)	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)		
CAE (e.g., FEA)	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)	(Y)	(N)
Rapid Prototyping (e.g. stereolithography)	(1)	(2)	(3)	(4)	(5)	(X)	(A)	(B)	(C)	(D)	(E)	(Y)	(N)
Electronic Data Interchange (EDI)	(1)	(2)	(3)	(4)	(5)	(X)						(Y)	(N)
LAN or Intranet	(1)	(2)	(3)	(4)	(5)	(X)						(Y)	(N)
WAN or Extranet	(1)	(2)	(3)	(4)	(5)	(X)						(Y)	(N)
Internet	(1)	(2)	(3)	(4)	(5)	(X)						(Y)	(N)

Section 2: Product Development Practices (1996-2001)

The following statements describe various product development practices. Please fill in the bubble that best represents the extent to which your firm employs each practice as applicable to your firm over the past 5 years.

		Not at all	A little	Moderately	Much	A great deal	Not Applicable
1	Process engineers are involved from the early stages of product development.	1	2	3	4	5	X
2	Our suppliers develop entire subassemblies for us.	1	2	3	4	5	X
3	Our product development people meet with customers.	1	2	3	4	5	X
4	Team members are cooperative with each other during the development of a product.	1	2	3	4	5	X
5	We study how our customers use our products.	1	2	3	4	5	X
6	Product development managers are given genuine authority over personnel.	1	2	3	4	5	X
7	Product development group members represent a variety of disciplines.	1	2	3	4	5	X
8	In developing product concepts, we listen to our customer needs.	1	2	3	4	5	X
9	Our suppliers do the product engineering of component parts for us.	1	2	3	4	5	X
10	Product development group members enjoy working in teams.	1	2	3	4	5	X
11	Our suppliers develop component parts for us.	1	2	3	4	5	X
12	We visit our customers to discuss product development issues.	1	2	3	4	5	X
13	Manufacturing plays a strong role in the design of products.	1	2	3	4	5	X
14	Our suppliers are involved in the early stages of product development.	1	2	3	4	5	X
15	In this firm, employees from different departments feel comfortable contacting each other.	1	2	3	4	5	X
16	Our core products are designed as platforms for multiple generations of products to come.	1	2	3	4	5	X
17	We ask our suppliers for their input on the design of component parts.	1	2	3	4	5	X
18	Team members are accountable to the product development team.	1	2	3	4	5	X
19	Product development managers derive their influence from expert knowledge of the manufacturing processes.	1	2	3	4	5	X
20	Team members are committed to developing superior products.	1	2	3	4	5	X
21	Product development employees work as a team.	1	2	3	4	5	X
22	Product development managers have enough influence to make things happen.	1	2	3	4	5	X
23	Various disciplines are involved from the early stages of product development.	1	2	3	4	5	X
24	Exposure to the information and perspectives of other departments help members think of new ideas about the product.	1	2	3	4	5	X
25	Product development managers have a final say in product design decisions.	1	2	3	4	5	X
26	There is opportunity for informal "hall talk" among individuals from different departments in this firm.	1	2	3	4	5	X
27	We make use of supplier expertise in the development of our products.	1	2	3	4	5	X
28	Product development group members share information.	1	2	3	4	5	X
29	Team members' rewards depend on how well they perform on the product development project.	1	2	3	4	5	X
30	Product development managers have broad influence across the organization.	1	2	3	4	5	X
31	Team members challenge the assumptions underlying each other's idea and perspectives.	1	2	3	4	5	X
32	Our product designs are drawn to accommodate future generations of products.	1	2	3	4	5	X
33	Team members are rewarded based on how well they perform on the product development project.	1	2	3	4	5	X
34	We involve our customers in the early stages of product development.	1	2	3	4	5	X
35	Product and process development designs are developed concurrently by a group of employees from various disciplines.	1	2	3	4	5	X
36	Manufacturing personnel participate early-on in product development phases.	1	2	3	4	5	X
37	Product development managers have a final say in budget decisions.	1	2	3	4	5	X
38	Manufacturing and product design personnel cooperate extensively.	1	2	3	4	5	X
39	Manufacturing is involved in the early stages of product development.	1	2	3	4	5	X
40	In this firm, it is easy to talk to virtually anyone, regardless of their rank or position.	1	2	3	4	5	X
41	Our product designs enable us to accommodate several generations of the same products.	1	2	3	4	5	X
42	Much of process design is done concurrently with product design.	1	2	3	4	5	X

Section 3: CAD Usage

The following statements describe typical types of CAD usage in a firm. Please fill in the bubble which best indicates your firm's extent of use in each manner (in Column A).

If a specific usage is rated "1= Not at all" or "2=A little" in Column A, then please fill the bubble(s) in column B that correspond(s) to the reason(s) why your firm is not using it more extensively.

		Column A Extent of Use					*Column B* Low use, why?				
		Not at all	A little	Moderately	Much	A great deal	Not a need	Function unavailable	Compatibility problems	Don't know how	Other
43	CAD files are used to facilitate servicing sales.	1	2	3	4	5	A	B	C	D	E
44	We rely on our customers for CAD files.	1	2	3	4	5	A	B	C	D	E
45	CAD is used to evaluate designs.	1	2	3	4	5	A	B	C	D	E
46	End-users in marketing retrieve specific CAD information and/or CAD files for their work.	1	2	3	4	5	A	B	C	D	E
47	We use CAD files provided by our customers.	1	2	3	4	5	A	B	C	D	E
48	CAD files are used as reference by functions throughout the firm.	1	2	3	4	5	A	B	C	D	E
49	Our suppliers rely on us for CAD files.	1	2	3	4	5	A	B	C	D	E
50	CAD is used to produce drawings for the customers.	1	2	3	4	5	A	B	C	D	E
51	End-users in manufacturing use CAD files for reference.	1	2	3	4	5	A	B	C	D	E
52	CAD is used to extract critical dimensions for quality control purposes.	1	2	3	4	5	A	B	C	D	E
53	Our suppliers provide us with the CAD files of the components they develop.	1	2	3	4	5	A	B	C	D	E
54	CAD files are accessible to functions throughout the firm.	1	2	3	4	5	A	B	C	D	E
55	Product engineers use CAD to show and to share product design ideas.	1	2	3	4	5	A	B	C	D	E
56	We rely on our suppliers for CAD files.	1	2	3	4	5	A	B	C	D	E
57	We develop the CAD files of a product for the customers.	1	2	3	4	5	A	B	C	D	E
58	End-users in production planning retrieve specific CAD information.	1	2	3	4	5	A	B	C	D	E
59	Our suppliers create the CAD files of components/parts.	1	2	3	4	5	A	B	C	D	E
60	CAD is used to test component interactions.	1	2	3	4	5	A	B	C	D	E
61	CAD files or a neutral format of CAD files are sent to the customers.	1	2	3	4	5	A	B	C	D	E
62	CAD is used to compile critical product specification dimensions.	1	2	3	4	5	A	B	C	D	E
63	We provide CAD files to our suppliers.	1	2	3	4	5	A	B	C	D	E
64	CAD is used to simulate design alternatives.	1	2	3	4	5	A	B	C	D	E
65	CAD is used to provide information for production planning.	1	2	3	4	5	A	B	C	D	E
66	Our customers rely on us for CAD files.	1	2	3	4	5	A	B	C	D	E
67	Our suppliers show us a component/part in realistic visual manner via CAD.	1	2	3	4	5	A	B	C	D	E

Section 4: Product Development Goals

Firms typically utilize CAD with certain implicit and explicit objectives for improving their product development performance. For each of the following objectives, please fill in the bubbles that indicate the level of achievement that represents your firm's target goal and your firm's actual accomplishment.

			Level of achievement				
			Limited	..	Moderate	..	Extensive
68	Reducing development time	Goal:	1	2	3	4	5
		Actual:	1	2	3	4	5
69	Improving design quality	Goal:	1	2	3	4	5
		Actual:	1	2	3	4	5
70	Improving development productivity	Goal:	1	2	3	4	5
		Actual:	1	2	3	4	5
71	Reducing product cost	Goal:	1	2	3	4	5
		Actual:	1	2	3	4	5
72	Reducing manufacturing cost	Goal:	1	2	3	4	5
		Actual:	1	2	3	4	5

Section 5: Operational Performance

The following statements measure various product development process performance and manufacturing performance. Please fill in the bubble that best indicates the extent to which you agree or disagree with each statement as applicable to your firm.

		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Not Applicable
73	Our teams develop high quality products.	1	2	3	4	5	X
74	Our product development teams use product engineering hours efficiently.	1	2	3	4	5	X
75	There has been decrease in material handling cost.	1	2	3	4	5	X
76	Our product development teams are productive.	1	2	3	4	5	X
77	Manufacturing processes are simple.	1	2	3	4	5	X
78	Outgoing products are delivered on time.	1	2	3	4	5	X
79	Setups of manufacturing system are simple.	1	2	3	4	5	X
80	Our product development teams use product development resources rationally.	1	2	3	4	5	X
81	Our products are easy to assemble.	1	2	3	4	5	X
82	Our teams develop product on schedule.	1	2	3	4	5	X
83	Product flow is streamlined.	1	2	3	4	5	X
84	Our teams' product development time has been reduced.	1	2	3	4	5	X
85	Manufacturing problems are easy to solve.	1	2	3	4	5	X
86	Work-in-progress inventories have decreased.	1	2	3	4	5	X
87	Our teams develop innovative products.	1	2	3	4	5	X
88	We have few manufacturing problems.	1	2	3	4	5	X
89	Our teams meet the target dates of our product development projects.	1	2	3	4	5	X
90	The quality of our outgoing products has increased.	1	2	3	4	5	X
91	Our product development teams are effective.	1	2	3	4	5	X
92	Production rework cost has declined.	1	2	3	4	5	X
93	The product development teams meet market introduction deadlines.	1	2	3	4	5	X
94	Production cost per unit of finished product has decreased.	1	2	3	4	5	X
95	Our product development teams use financial resources sensibly.	1	2	3	4	5	X

Section 6: Comparative Performance

The following statements measure your firm's capability to customize products inexpensively and quickly. Please fill in the bubble that best indicates your perception of the relative capabilities of your firm as compared to the industry average.

		Much Below Average	Below Average	About Average	Above Average	Much Above Average
96	Our capability of customizing products at low cost is	1	2	3	4	5
97	Our capability of customizing products on a large scale is	1	2	3	4	5
98	Our capability of translating customer requirements into technical design quickly is	1	2	3	4	5
99	Our capability of adding product variety without increasing cost is	1	2	3	4	5
100	Our capability of customizing products while maintaining a large volume is	1	2	3	4	5
101	Our capability of setting up for a different product at a low cost is	1	2	3	4	5
102	Our capability of responding to customization requirements quickly is	1	2	3	4	5
103	Our capability of adding product variety without sacrificing overall production volume is	1	2	3	4	5
104	Our capability of changeover to a different product quickly is	1	2	3	4	5
105	Our capability of producing customized products with lead time and cost comparable to mass- produced products is	1	2	3	4	5

The following statements pertain to the development time in four phases of product development. Please fill in the bubble that best indicates your perception of the relative time performance of your firm as compared to the industry average.

		Longest	..	Average	..	Shortest
106	My firm's concept generation time is	1	2	3	4	5
107	My firm's product design time is	1	2	3	4	5
108	My firm's product testing and refinement time is	1	2	3	4	5
109	My firm's manufacturing production time is	1	2	3	4	5

Section 7: Overall Performance

The following statements measure the value of your products to customers over the past five years. Please fill in the bubble that best indicates the extent to which you agree or disagree with each statement.

	Statement	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Don't Know
110	Our customers are satisfied with the quality of our products.	①	②	③	④	⑤	ⓧ
111	Our customers are satisfied with the features that our products provide.	①	②	③	④	⑤	ⓧ
112	Our customers are loyal to our products.	①	②	③	④	⑤	ⓧ
113	Our customers refer new customers to purchase our products.	①	②	③	④	⑤	ⓧ
114	Our customers feel that we offer products with high value.	①	②	③	④	⑤	ⓧ
115	Our customers perceived that they received their money's worth when they purchased our products.	①	②	③	④	⑤	ⓧ

Section 8: General Information

116. Your job title: [ ]

117. What is your level of knowledge about your firm's use of CAD and its impact?
O Very Knowledgeable O Knowledgeable O Somewhat Knowledgeable O Little or no knowledge

118. How long has your firm been using CAD? [ ] (number of years) OR since [ ] (year).

119. How many employees does your firm/division have?
O Less than 100 O 100-499 O 500-999 O 1000-2499 O More than 2500

120. Which one of the following two digits Standard Industrial Classification (SIC) code best applies to your firm's industry?
O 30 = Rubber & Misc. Plastics O 34 = Primary Metal Industries O 35 = Fabricated Metal Products
O 37 =Transportation Equipment O 38 = Measuring & Analyzing Instruments O Other:__________

121. Please indicate the annual sales of your firm.
O Less than $10 million O $10 to < $50 million O $50 to <$100 million O $100 to <$250 million
O $250 to < $500 million O $500 to <$1000 million O $1000 million and above

122. What percentage of your products are: [%] Make to order? [%] Make to stock?

123. What percentage of your products are: **commodity** products? [%] **Detail-controlled** products? [%]
Proprietary technology products? [%] **Highly customized** products? [%]

124. What is the primary or dominant manufacturing process of your firm?
O Continuous flow process O Flexible Manufacturing O Assembly line O Job shop
O High volume, discrete part production O Manufacturing cells O Batch processing O Projects (one-of-a-kind)

125. What percentage of your firm's sales comes from B2B e-commerce transactions? [%]

126. What percentage of the following products (in dollar value) are currently purchased through B2B e-commerce?
Raw material [%] Parts/Components [%] Office Supplies [%] Other [%]

127. Which one of the following statements best characterize you firm's adoption of B2B e-commerce?
O We were first in our industry sector to do it.
O We were about 1 year behind the first in our industry sector to do it.
O We adopted it at the same time as most of our competitors did.
O We waited until most of our competitors were doing it, then jumped in when it was a "sure thing".
O We are in the process of implementing B2B e-commerce.
O We are planning implementation of B2B e-commerce in the near future.
O We are not considering adoption of B2B e-commerce in the near future.

Appendix 2: Final list of items retained in each Measurement Model

Items retained for Product Development Practices	
	Heavyweight Product Development Manager (construct reliability= 0.786, variance extracted=0.48)
HM1	Product development managers are given "real" authority over personnel.
HM4	Product development managers have a final say in budget decisions.
HM5	Product development managers have a final say in product design decisions.
HM6	Product development managers have broad influence across the organization.
HM2*	Product development managers have enough influence to make things happen. (Domain covered by HM6)
HM3*	Product development managers derive their influence from expert knowledge of the manufacturing processes. (Domain covered by HM5 and HM6)
	Concurrent engineering: team (construct reliability= 0.721, variance extracted=0.56)
CE1	Product development employees work as a team.
CE3	Product development group members share information.
	Concurrent engineering: concurrent product-process development (construct reliability= 0.727, variance extracted=0.47)
CE4	Much of process design is done concurrently with product design.
CE6	Manufacturing is involved in the early stages of product development.
CE7	Process engineers are involved from the early stages of product development.
CE5	Product and process development designs are developed concurrently by a group of employees from various disciplines.
	Concurrent engineering early involvement of various disciplines**
CE8	Various disciplines are involved from the early stages of product development.
CE2*	Product development group members represent a variety of disciplines. (Domain covered by CE8)
	Platform Products (construct reliability= 0.871, variance extracted=0.69)
PP1	Our core products are designed as platforms for multiple generations of products to come.
PP2	Our product designs enable us to accommodate several generations of the same products.
PP3	Our product designs are drawn to accommodate future generations of products.
	Customer Involvement (construct reliability= 0.827, variance extracted=0.62)
CI1	We involve our customers in the early stages of product development.
CI3	We visit our customers to discuss product development issues.
CI5	Our product development people meet with customers.
CI2*	In developing product concept, we listen to our customer needs. (Domain covered by CI5)
CI4*	We study how our customers use our products. (Domain covered by CI3 and CI5)
	Supplier Involvement**
SI4	Our suppliers are involved in the early stages of product development.
SI5*	We ask our suppliers for their input on the design of component parts. (Domain covered by SI4)
SI6*	We make use of supplier expertise in the development of our products. (Domain covered by SI4)
SI1*	Our suppliers do the product engineering of component parts for us. (Deals with suppliers' product development as opposed to the responding firm's)
SI2*	Our suppliers develop the component parts for us(Deals with suppliers' product development as opposed to the responding firm's)
SI3*	Our suppliers develop the whole subassemblies for us. (Deals with suppliers' product development as opposed to the responding firm's)

* Items not retained (reason for deletion)

** Single item construct, construct reliability and variance extracted cannot be calculated.

Items retained for CAD Usage	
	CAD USAGE: Engineering Design (construct reliability= 0.794, variance extracted= 0.57)
ED2	CAD is used to simulate design alternatives.
ED3	CAD is used to test component interactions.
ED4	Product engineers use CAD to show and to share product design ideas.
ED1*	CAD is used to evaluate designs. (Domain covered by ED2)
	CAD USAGE: Cross functional (construct reliability= 0.722, variance extracted= 0.47)
CF1	CAD files are accessible to other functions within the firm.
CF3	End-users in production planning retrieve specific CAD information.
CF4	End-users in marketing retrieve specific CAD information and/or CAD files for their work.
CF2*	End-users in manufacturing use CAD files for reference. (Domain covered by CF3)
	CAD USAGE: Integrate with Customers (construct reliability= 0.859, variance extracted= 0.67)
IC2	CAD files or neutral format of CAD files are sent to the customers.
IC3	We develop the CAD files of a product for the customers.
IC4	Our customers rely on us for CAD files.
IC1*	CAD is used to produce drawings for the customers. (Domain covered by IC2 and IC4).
IC6*	We use CAD files provided by our customers. (Deals with customers' usage of CAD)
IC5*	We rely on our customers for CAD files. (Deals with customers' usage of CAD)
	CAD USAGE: Integrate with Suppliers (construct reliability= 0.862, variance extracted= 0.61)
IS1	Our suppliers create the CAD files of our components/parts.
IS2	Our suppliers show us a component/part in realistic visual manner via CAD.
IS3	Our suppliers provide us the CAD files of the components they developed.
IS4	We rely on our suppliers for CAD files.

* Items not retained (reason for deletion)

Items retained for Firm Performance	
	Product Development Process Performance: Team Process Outcome (construct reliability= 0.881, variance extracted=0.71)
TP1	The product development teams meet market introduction deadlines.
TP2	Our teams developed product on schedule.
TP4	Our teams meet the target dates of our product development project.
TP3*	Our teams' product development time has been reduced. (Deals with product development time)
TP5*	Our teams developed innovative products. (Deals with the product outcome)
TP6*	Our teams developed high quality products. (Deals with the product outcome)
	Product Development Process Performance: Team Efficiency (construct reliability= 0.860, variance extracted=0.61)
TE1	Our product development teams are productive.
TE2	Our product development teams use financial resources sensibly.
TE4	Our product development teams use product engineering hours efficiently.
TE5	Our product development teams are effective.
TE3*	Our product development teams use product development resources rationally. (Domain covered by TE1, TE2, TE4 and TE5)
	Manufacturing Effectiveness (construct reliability= 0.788, variance extracted=0.48)
MP6	Product flow is streamlined.
ME1	Production rework cost has declined.
ME2	Production cost per unit of finished product has decreased.
ME4	There has been decrease in material handling cost.
MP2*	We have few manufacturing problems. (Domain covered by MP6 and ME1)
ME3*	Work-in-progress inventories have decreased. (Domain covered by MP6 and ME4)
ME5*	The quality of our outgoing products has increased. (Domain covered by ME1)
ME6*	Outgoing products are delivered on time. (Domain covered by ME4)
	Overall Firm Performance: Value to Customer (construct reliability= 0.805, variance extracted=0.58)
VC4	Our customers refer new customers to purchase out products.
VC5	Our customers feel that we offer products with high value.
VC6	Our customers perceived that they received their moneys' worth when they purchased our products.
VC1*	Our customers are satisfied with the quality of our products. (Domain covered by VC5 and VC6)
VC2*	Our customers are satisfied with the features that our products provide. (Domain covered by VC5)
VC3*	Our customers are loyal to our products. (Domain covered by VC4)

* Items not retained (reason for deletion)

Appendix 3: Step-by-step CFA

Heavyweight Product Development Managers

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	HM1 to HM6	24.98	9	.101	0.059	.94	.96	
2 To Retain	HM1, HM2, HM4-HM6	9.67	5	.073	0.036	.97	.98	

1. The hypothesized model (Model 1) is rejected. The error terms for HM3 is correlated with those of HM2 and HM4 with MIs = 10.38 and 8.61 respectively; and the error terms of HM4 and HM5 are correlated at MI = 8.58. Since item HM3 has the lowest loading of 0.51 and its domain is also covered by items HM5 and HM6, item HM3 is eliminated.

2. Model 2 has good fit indices and is not rejected.

Concurrent Engineering

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	CE1 to CE8	77.25	20	.128	0.074	.83	.88	
2	(CE1,CE3), (CE4 to CE7), (CE2,CE8)	30.38	17	.067	0.049	.95	.97	
3 To Retain	(CE1,CE3), (CE4, CE6,CE7), (CE2,CE8)	9.45	11	.000	0.025	1.01	1.00	

1. The hypothesized model (Model 1) is rejected. The error terms for CE2 and CE8 are correlated with modification index (MI) of 9.23; the error terms of CE4, CE6 and CE7 are intercorrelated with MIs = 13.78, 9.28 and 18.71; and the error terms of CE1 and CE3 are correlated with MI = 13.28. The wordings in the groups of correlated items correspond with the three underlying facets of concurrent engineering, which are: team, concurrent product and process development, and early involvement. Hence, this construct is reconceptualized as consisting of three dimensions with item CE5, based on the wording of the item, being included as an indicator of concurrent product and process development.

2. Model 2 has good fit indices, however, item CE5 cross loaded on the other two dimensions (team and early involvement) with MIs = 11.69 and 19.16. Furthermore CE5 has the lowest loading value on the concurrent product and process development dimension. Hence, item CE5 is eliminated.

3. Model 3 has good fit indices and is retained.

Platform Products

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1 To Retain	PP1 TO PP3	N/A	N/A	N/A	N/A	N/A	N/A	.8699

CFA in LISREL cannot evaluate models with three items or less. Hence, using the factor analysis procedure on SPSSX, the three items factor extracted explains 77.65% of the total variance.

Customer Involvement

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	CI1 to CI5	16.71	5	.116	0.044	.92	.96	
2 To Retain	CI1, CI2, CI3, CI5	2.00	2	0	0.015	1.00	1.00	

1. The hypothesized model (Model 1) is rejected, the error terms of CI2 and CI4 are correlated with MI = 11.33. Since item CI4 has a lower loading than item CI2 at 0.52, and the domain in item CI4 is also covered CI3 and CI5, hence it is eliminated.

2. Model 2 has good fit indices, and is not rejected.

Supplier Involvement

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	SI1 to SI6	60.65	9	.182	0.089	.67	.80	
2 To Retain	SI4 to SI6	NA	NA	NA	NA	NA	NA	.6706

1. The hypothesized model (Model 1) has poor fit indices and is rejected. The error terms of SI1 and SI2 are highly correlated with MI = 36.76. Closer examination of the wordings in the items suggests items SI, SI2 and SI3 deals specifically with the product development performed by the suppliers with no qualifier for collaboration with the responding firm. Hence, these item were eliminated.

2. CFA in LISREL cannot evaluate models with three items or less. Hence, using the factor analysis procedure on SPSSX, the three items factor extracted explains 59.2% of the total variance.

Product Development Practices

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI
1	22 items: (HM1,2,4 to 6), (CE1,3), (CE4,5,7), (CE2,8), (PP1-3), (CI1-3,5), (SI4-6)	312.78	188	.062	.063	.90	.92
2	21 items: delete CI2	265.55	168	.058	.059	.91	.93
3	20 items:-CI2, HM2	224.78	149	.054	.058	.92	.94
4	19 items:-CI2,HM2, SI6	174.79	131	.044	.056	.94	.95
5	18 items:-CI2,HM2, SI6, SI5 or 17 items:-CI2,HM2, SI6, SI4-5	161.10 152.09	115 104	.048 .057	.056 .057	.94 .94	.95 .95
6	17 items:-CI2,HM2, SI6, SI5, CE2 or 15 items:-CI2,HM2, SI6, SI4-5,CE2-8	142.92 126.44	100 80	.050 .058	.056 .060	.94 .93	.96 .96

1. The hypothesized model (Model 1) has acceptable fit indices. However, item CI1 cross loads on Platform Products (MI=25.20), Team (MI=22.37) and Early Involvement (MI=5.61) dimensions of Concurrent Engineering, and Supplier Involvement (MI=9.72) practices. It is the lowest loading indicator of Customer Involvement (0.67) and its domain is covered by CI5, hence, item CI2 is eliminated.

2. Model 2 has acceptable fit indices. Item HM2 is to be eliminated next since it cross loads on Team (MI=17.95) dimension of Concurrent Engineering and its domain is covered by HM6.

3. Model 3 has better fit indices than Model 2. However, the error terms of items SI6 and CE3 are correlated with MI=24.51. Since Supplier Involvement has one more indicator than the Team dimension of Concurrent Engineering, item SI6 is eliminated.

4. Model 4 has better fit indices than Model 3. There are four pairs of correlated error terms: three pairs involve Heavyweight Product Development Manager indicators and one pair between the Customer Involvement indicators. The largest MI is 10.95. In addition, the loadings of items SI5 and CE2 are low (0.53 and 0.57 respectively). Hence, item SI5 is selected for the next elimination (its domain is covered by the remaining single indicator of Supplier Involvement).

5. Model 5 has good fit indices. Item CE2 is eliminated next due to low loading (0.59).

6. Model 6 has good fit indices and all items have loadings above 0.60.

Engineering Design Usage

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1 **To Retain**	ED1 to ED4	1.32	2	0	0.023	1.01	1.00	

1. The hypothesized model (Model 1) has good fit indices and is not rejected.

Cross Functional Usage

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1 **To Retain**	CF1 to CF4	6.46	2	.113	0.068	.91	.97	

1. The hypothesized model (Model 1) has acceptable fit indices and is not rejected.

Integrate with Customers Usage

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	IC1 to IC6	124.14	9	.271	0.23	.52	.71	
2	IC1 to IC4	8.99	2	.142	.064	.93	.98	
3 **To Retain**	IC2 to IC4	NA	NA	NA	NA	NA	NA	0.8548

1. The hypothesized model (Model 1) has poor fit indices and is rejected. The error terms for items IC5 and IC6 are highly correlated with a modification index of 99.97. The error terms for IC1 and IC3 are also correlated with MI=10.47. Close examination of the wordings suggests IC5 and IC6 specifically deals with CAD files created by the customers and are inconsistent with the other indicators of the firm performing the CAD work for the customers. Hence items IC5 and IC6 are eliminated.

2. Model 2 does not have good fit indices and is rejected. The lowest loading item (C1 has a loading of 0.64) is a candidate for elimination.

3. CFA in LISREL cannot evaluate models with three items or less. Hence, using the factor analysis procedure on SPSSX, the three items factor extracted explains 77.72% of the total variance (an increase from the variance explained using the four items – 70.31%).

Integrate with Suppliers Usage

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1 To Retain	IS1 to IS4	2.58	2	.041	.021	.99	1.00	

1. The hypothesized model (Model 1) has good fit indices and is not rejected.

CAD USAGE

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI
1	15 items: (ED1-4),(CF1-4),(IC2-4),(IS1-4)	117.11	84	.048	.093	.95	.96
2	14 items: - CF2	89.61	71	.038	.084	.97	.98
3	13 items: - CF2, ED1	74.09	59	.038	.081	.98	.98

1. The hypothesized model (Model 1) has acceptable fit indices. However, the error terms of items CF2 and CF4 are correlated with MI=12.27. Since he domain of CF2 is covered by CF3, it is eliminated next.

2. Model 2 has better fit indices than Model 1. Item ED1 has a low loading of 0.60, its domain is covered by ED2. Hence, it is eliminated next.

3. Model 3 has better fit indices than Model 2.

Manufacturing Effectiveness

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	MP2, MP6, ME1-ME6	32.81	20	.061	0.038	.94	.96	
2 To Retain	MP2, MP6, ME1-ME4, ME6	15.06	14	.021	0.034	.99	.99	

1. The hypothesized model (Model 1) has good fit indices, however, the error terms for ME1 and ME5 are correlated with MI=12.39. Since ME5 has the lower loading (0.64), it is eliminated.

2. Model 2 has good fit indices and is not rejected.

PD Process Performance: Team Process Outcome

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	TP1 to TP6	35.90	9	.13	0.047	.89	.93	
2	TP1 to TP4	6.69	2	.116	0.026	.96	.99	
3 To Retain	TP1, TP2, TP4	NA	NA	NA	NA	NA	NA	.879

1. The hypothesized model (Model 1) has poor fit indices and is rejected. Close examination of the wordings of items TP5 and TP6 shows "innovative product" and "quality product" deal with the product outcome rather than the process outcome. Hence, these items are eliminated.

2. Model 2 does not have good fit indices and is rejected. The wording in the lowest loading item (TP3 has a loading of 0.52) deals with product development time in its entirety with no clear adherence to planned time schedule. Therefore, item TP3 is a candidate for elimination.

3. CFA in LISREL cannot evaluate models with three items or less. Hence, using the factor analysis procedure on SPSSX, the three items factor extracted explains 78.88% of the total variance (an increase from the variance explained using the four items – 67.85%)

PD Process Performance: Team Efficiency

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	TE1 to TE5	14.89	5	.107	0.024	.95	.98	
2 To Retain	TE1,TE2,TE4,TE5	.01	2	0	0.001	1.02	1.00	

1. The hypothesized model (Model 1) has acceptable fit indices, however, the error terms of items TE2 and TE3 are correlated with MI=11.49. Since the domain in item TE3 is covered by item TE2 and TE4, TE3 is eliminated.

2. Model 2 has good fit indices and is retained.

Value to Customer

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI	α
1	VC1 to VC6	34.67	9	.128	0.030	.87	.92	
2	VC1 , VC3 to VC6	16.43	5	.115	0.026	.92	.96	
3	VC1, VC4 to VC5	.18	2	0	0.002	1.02	1.00	.7923
4 To Retain	VC4 to VC6							.7838

1. The hypothesized model (Model 1) has poor fit indices and is rejected. Close examination of the wordings in items VC1 and VC2 suggests these items deal with customers' satisfaction. Furthermore, their error terms are correlated with MI=12.27. Item VC2 is eliminated because its domain is covered by VC1.

2. Model 2 has unacceptable fit indices, the error terms of items VC3 and VC4 are correlated with MI=13.87. Examination of the wordings in these items suggests both items deal with increase customer order, VC3 based on existing customer loyalty

and VC4 based on referral by existing customer. Since the domain in VC4 is broader and more general than domain in VC3, item VC3 is eliminated.

3. Model 3 has good fit indices, however, item VC1 has a low loading (0.56) and therefore is a candidate for elimination.

4. CFA in LISREL cannot evaluate models with three items or less. Hence, using the factor analysis procedure on SPSSX, the three items factor extracted explains 69.97% of the total variance (an increase from the variance explained using the four items - 61.51%).

Firm Performance

Model #	Measurement Item	χ^2	d.f	RMSEA	RMR	NNFI	CFI
1	17 items: (MP2,6,ME1-4,6),(TP1,2,4), (TE1,2,4,5),(VC4-6)	181.06	113	.059	.048	.93	.94
2	16 items: - ME6	146.59	98	.053	.040	.94	.95
3	15 items: - ME6, MP2	125.68	84	.053	.037	.95	.96
4	14 items: - ME6, MP2, ME3	107.05	71	.054	.036	.95	.96

1. The hypothesized model (Model 1) has acceptable fit indices. However, item ME6 cross loads on Team Process Outcome with MI=21.51. Hence, ME6 is eliminated.

2. Model 2 has better fit indices than Model 1. Item MP2 also cross loads on Team Process Outcome with MI=8.47. Hence, MP2 is eliminated next.

3. Model 3 has better fit indices than Model 2. However, item ME3 has a low loading of 0.43. Hence, ME3 is eliminated next.

4. Model 4 has good fit indices and is not rejected.