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**PRODUCT COMPLEXITY: THEORETICAL RELATIONSHIPS TO DEMAND AND SUPPLY CHAIN COSTS**

presented by

Mark A. Jacobs

has been accepted towards fulfillment
of the requirements for the

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Major Professor's Signature

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# PRODUCT COMPLEXITY: THEORETICAL RELATIONSHIPS TO DEMAND AND SUPPLY CHAIN COSTS

BY

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# ABSTRACT

## PRODUCT COMPLEXITY: THEORETICAL RELATIONSHIPS TO DEMAND AND SUPPLY CHAIN COSTS

By

Mark A. Jacobs

Researchers have suggested that product portfolio complexity effects firm performance but that the effects are not well understood. This study enhances the understanding by clearly defining the construct, developing a typology, applying the theoretical framework of Theory of Performance Frontiers, developing measures or complexity factors descriptive of the construct, and testing several hypotheses informed by the definition and theoretical perspective.

From a thorough grounding in the literature, product portfolio complexity is defined to be the state of possessing a multiplicity of, and relatedness among, products within the portfolio. Complexity is found to possess two dimensions: multiplicity and relatedness. Relatedness contains three subdimensions: similarity, interconnectedness, and complementarity.

Several measures of multiplicity and similarity are created and are informed by the definition and theoretical perspective. Hypotheses which relate these measures to various costs and sales volume are tested using panel data regression by analyzing longitudinal

product portfolio and cost data provided by a designer and manufacturer of data processing equipment.

The results reveal that measures of multiplicity are more effective at predicting cost than measures of similarity. Additionally, models measuring changes in cost or volume rather than absolute levels are superior. On average, complexity variables used to measure changes in cost or volume explain 10% of variance and the full models explain over 50%.

Thus this research fills a portion of the gap in understanding that exists about the relationship between product portfolio complexity and firm performance by providing a theoretically grounded understanding of complexity's relationship to cost and sales volume. Further, a typology of complexity is developed, two of its dimensions operationalized, and the Theory of Performance Frontiers extended to intangible assets. Beyond the academic contribution of the research is the benefit offered to the business community. Specifically, this research provides an approach to quantifying the most profitable configuration of a portfolio. Thus the research both advances theory and offers benefit to the practitioner community.

# Dedication & Acknowledgments

There are few things that stand in isolation. Most are related to something else at least at some point. In the case of this undertaking, there are many connections of differing kinds; thus it manifests the very construct it seeks to explicate. Herb Simon informed us in 1961 that nearly every system is decomposable to integrated parts. In the case of this research, some of those parts are apparent and some not. The apparent parts are called attention to in the bibliography; the foundation of knowledge provided by prior scholars. The parts that are not apparent are many and a few of the most significant are highlighted below.

The seed was planted for the pursuit of doctoral studies when as a young child I watched my father earn his doctorate. I learned of the doctoral status of my uncles and finally of the doctoral studies of my mother. I was inculcated in the value of education through living in graduate student housing while my father earned his doctorate, being raised in a neighborhood populated by physicians after he completed the degree, and by the constant reminding by my parents of the importance of education. This initial push and the expectation of attaining my personal best has enabled me to be in a position to undertake this dissertation.

Later in life I was exposed to three academics who cast a vision of a career in academia. The first was Ralph Morgan, for whom I worked on a research project while at Cal Poly. He encouraged me to pursue graduate studies, but I fancied myself following a path more similar to his own; several years running a business and then later earning a doctorate and entering academia. The second and third were Fred Beier for whom I also worked on a research project while at the University of Minnesota and my uncle, Carl Adams. Fred and Carl were generous with their time and instrumental in helping me work through the decisions of whether and where to pursue a doctorate and if a life in academia was right for me. Without the assistance and advice of Fred and Carl and the example of Ralph Morgan, it is unlikely I would be writing this dissertation.

The faculty at Michigan State, in particular my two advisors Morgan Swink and Shawnee Vickery, have prepared me well to execute this dissertation and prosecute a productive research agenda. Without their training and in particular the guidance of Morgan Swink, my committee chair, this research could not have been undertaken. Morgan has been captain, coach, cheerleader, counselor, critic, and comrade at various and appropriate times. I am indebted to him for the investments he has made in my development as a scholar. I am also indebted to my committee, Roger Calantone, Dave Close, and Bob Hubbard for their contributions in funding and reviewing this research, advising me in its execution, and encouragement along the way.

The most important connection to this research is my wife Barbara and daughters Sarah and Laura. Their willingness to forego the luxuries of life, move away from family and friends, and tolerate my stress levels and work schedule throughout a seven year transition period has allowed this dissertation and ultimately the doctorate to be realized. Barbara in particular has made sacrifices which are too many to list. Her support and belief in me, more than any other reasons, are why this dissertation has been completed. Without them, none of the events above would have mattered.

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## 1.0 Overview of the research

### 1.1 Introduction

The proposed dissertation draws upon engineering, marketing, and supply chain literatures to develop theoretical explanations for product complexity's impact on components of product demand and various supply chain costs. Specifically, this research focuses on the dimensions of complexity represented in business unit product portfolios reflecting the design and manufacturing of tangible, discrete, assembled products. Hypotheses which specifically relate portfolio complexity factors to product demand and supply chain outcomes are tested using historical product, sales, and cost data. This is the first research to empirically assess the effects of multiple dimensions of product complexity on both sales volume and cost in a large scale manner.

This chapter is organized as follows. First, the concept of product complexity is defined. Then the motivation for performing the research is discussed. The hypotheses are presented and discussed next followed by a discussion of the methodology. The chapter concludes by discussing the research contributions.

The subsequent chapters address in greater detail the topics introduced in this chapter. Chapter Two provides significant detail regarding the current literature. Chapter Three provides the theoretical underpinning of the research and formally presents the research hypotheses. Chapter Four describes the research design. Chapter Five reviews the analysis process and results. Chapter Six offers the conclusions and management implications.

## 1.2 Objectives

There are multiple objectives for this research. The first is to develop a robust definition of the construct 'complexity'. Second is the development of a typology that contextualizes current and future research on the topic. Third is the establishment of the functional forms of various dimensions of complexity in regards to cost and sales volume.

## 1.3 Definitions

For science to advance at the maximal rate, there must be consensus (Kuhn, 1963). There must be commonly used definitions and descriptions of the phenomenon under consideration (Wacker, 2004). The study of product complexity has been hampered by the lack of a precise definition. My goal is to establish a basis for consensus beginning with a formal and robust definition of the construct 'complexity'. To do so I investigate several different disciplines to gain a comprehensive understanding of how complexity has been conceptualized. These findings are discussed below and summarized in Table 1.

Whereas the concept of a *product portfolio* is well defined and understood to be the complete set of possible product configurations offered by a business unit at a given point in time (McGrath, 2001; Meyer & Lehnerd, 1997), consensus regarding a definition of complexity has yet to emerge, possibly in part because complexity is a multifaceted concept. To begin the process of developing a formal definition of complexity, one place to look is in a dictionary. Therein, Webster (1964) defines complexity as "1a: the quality or state of being composed of two or more separate or analyzable items, parts, constituents, or symbols 2a: having many varied parts, patterns or elements, and consequently hard to understand fully 2b: marked by an involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with". Thus the complexity of an item stems from a *multiplicity* of elements, as well as from *relationships* among those elements expressed in "patterns" and "involvement." Further, this combination of multiplicative and relational aspects creates difficulties requiring resources (e.g., mental or otherwise) to be expended in order to achieve comprehension, or *processing*, of the item in question. These dimensions, multiplicity and relatedness, have been addressed in a variety of academic disciplines including product design, organizational design, chemistry, complex systems, and others.

### 1.31 Product Design

The product design literature consistently associates multiplicity with complexity. For example, Baldwin and Clark (2000) maintain that the complexity of a system is proportional to the total number of design decisions required (Baldwin & Clark, 2000). The association of complexity with multiplicity also relates to the context of product features (Griffin, 1997b) and components (Gupta & Krishnan, 1999). Kaski and Heikkila (2002) also focus on multiplicity, in the context of physical modules, but add that the degree to which they exhibit dependency is also related to product complexity.

1.32 Organizational Design

Organizational design researchers refer to complexity as the number of structural components that are formally distinguished (Blau & Shoenherr, 1971; Price & Mueller, 1986), the degree to which the structures are differentiated (Price & Mueller, 1986), or the number of elements which must be addressed simultaneously (Scott, 1992). Similarly, Daft (1983) states that the number of activities or subsystems within the organization influences complexity. He goes on to indicate that these activities or subsystems could be reflected in the number of levels in the organizational chart, departments within a division, or geographical diversity; thus touching on the hierarchical nature of complex systems.

1.33 Complex Systems

Both Boulding (1956) and Simon (1962) address the concept of multiple levels of complex systems. Simon (1962) identifies hierarchy as a means to describe more clearly the complexity inherent within the system. The complex systems literature also addresses complexity in terms of differentiation and connectivity (Klir, 1985). This is a parsing of Simon's (1962) original notion that a complex system is one comprised of a large number of parts that interact in a non-simple way.

1.34 Business

Hill (1972; 1973) typifies the marketing perspective in suggesting that product complexity is a result of product diversity, technology, newness, and bundled attributes such as after sales service. Very similar to the marketing perspective is that of

Management Information Systems which considers the depth and scope of required technical activities in assessing the degree of complexity (Meyer & Curley, 1991). The project management literature considers projects that have many varied inter-related parts as complex (Baccarini, 1996). These are all similar in that they tap the underlying dimensions of multiplicity and relatedness.

### 1.35 Hard Sciences

The disciplines of Chemistry and Physics pay particular attention to the connections between entities. Chemists use the term complex when referring to a state in which certain transition metals share electrons from one of the metal's outer valences with one or more anions (Kotz & Treichel, 1996; Whitten & Gailey, 1984). Researchers in both computational physics and evolutionary biology associate complexity with the degree of coupling or interactions among the elements within a system (Dooley & Van de Ven, 1999). It is these connections that are implied by Operations Research scholars when they refer to constraints; the more constraints represented in a problem, the greater the complexity (Eglese, Mercer, & Sohrabi, 2005).

### 1.36 Decision Sciences

Information processing theory suggests that complexity is a function of the diversity of information and the rate of information change (Campbell, 1988). Similarly, Wood (1986) reports that complexity is a function of the number of information cues that must be processed.

1.37 Operations Management

The operations management literature suggests the existence of two dimensions of complexity; I have characterized them as multiplicity and relatedness. Multiplicity and relatedness are represented in the characterization of supply chain complexity as a reflection of the number of parts and the degree of unpredictability (Bozarth, Warsing, Flynn, & Flynn, 2007); note that unpredictability is a function of the interconnections between the parts because as the number of connections increase the number of potential outcomes increases. Of the concepts of multiplicity and relatedness, the more developed of the two dimensions is multiplicity which is conceptualized most frequently in the literature as the number of components (Gupta & Krishnan, 1999; Ramdas, 2003). Complexity is considered to increase as the number of components increases. This is reported to be the case whether it is total part count (Novak & Eppinger, 2001) or number of unique parts (Collier, 1981; Rutenberg, 1971; Rutenberg & Shaftel, 1971). The same principle of increased number is manifested at the product level. Griffin (1997a) and Du, Jiao and Tseng (2001) report that the number of options or features represented within a product is another dimension of multiplicity. The last manifestation addressed is at the portfolio level. Ulrich (1995) and Randall and Ulrich (2001) identify the number of product versions as a dimension of multiplicity. This is articulated by Ramdas (2003) as product mix. Related to the product mix is the rate at which the products within the portfolio are replaced; the more frequent, the higher the complexity (Fisher, Ramdas, & Ulrich, 1999). The other main dimension of complexity is that of relatedness. The degree to which components, subassemblies, or other architectural representations are interconnected is a representation of relatedness; thus complexity is proportional to interconnectedness (Novak & Eppinger, 2001; Tatikonda & Stock, 2003).

**Table 1**
**Complexity Definitions**

| **Discipline** | **Source** | **Definition: Complexity is** |
|---|---|---|
| Rhetoric | Webster (Webster, 1964) | 1a: the quality or state of being composed of two or more separate or analyzable items, parts, constituents, or symbols 2a: having many varied parts, patterns or elements, and consequently hard to understand fully 2b: marked by an involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with. |
| Product Design | Baldwin & Clark (2000) | Proportional to the total number of design decisions |
| | Griffin (1997a; Griffin, 1997b) | The number of functions designed into a product |
| | Kaski & Heikkila (2002) | Represented by the number of physical modules and also by the degree of dependency |
| | Gupta & Krishnan (1999), Ramdas (2003) | The number of components |
| | Tatikonda & Stock (2003) | Proportional to the interdependence of technologies |
| Organizational Design | Blau & Schoenherr (1971) | The number of structural components that are formally distinguished |
| | Price & Mueller (1986) | The degree of formal structural differentiation |
| | Daft (1983) | Number of activities or subsystems across levels or geographies |
| | Scott (1992) | The number of elements that must be addressed simultaneously |
| Complex Systems | Simon (1962) | A system comprised of a large number of parts that interact in a non-simple way |
| | Flood & Carson (1988) | Difficult to understand |
| | Klir (1985) | A system manifesting differentiation and connectivity |

**Table 1**
**Continued**

| | | |
|---|---|---|
| Marketing | Hill (1972; Hill, 1973) | The degree of product standardization, technology complexity, newness of product, amount of purchase history, newness of application, installation ease, and amount of after sales service required |
| Management Information Systems | Meyer & Curley (1991) | The depth and scope of technical activities required |
| Project Management | Baccarini (1996) | A project comprised of many varied interrelated parts |
| Chemistry | Whitten & Gailey (1984), Kotz & Treichel (1996) | The sharing of valence electrons by certain transition metals with one or multiple anions |
| Physics & Biology | Dooley & van de Ven (1999) | The degree of coupling or interactions among the elements within the system |
| Operations Research | Eglese, Mercer, and Sohrabi (2005) | A synonym for constraint or difficulty; the more constraints represented in a problem, the more complex it is |
| Information Processing Theory | Gailbraith (1977) | The difference between information required and present to perform a task |
| | Wood (1986) | The number of information cues which must be processed |
| | Campbell (1988) | A function of the diversity of information and the rate the information changes. |
| Supply Chain Operations Management | Choi & Kraus (2006) | Manifested in varied number of types of suppliers and their interactions |
| | Bozarth, Warsing, Flynn & Flynn (2007) | The number of parts and the degree of unpredictability. |
| | Fisher, Ramdas & Ulrich (1999) | Manifested in number of systems and the rate at which products in the portfolio are replaced |
| | Novak & Eppinger (2001) | Represented by three facets: number of components, extent of interactions, and degree of product novelty |
| | Rutenberg & Shaftel (1971) | Represented by the number of modules and markets |

Based upon a review of the literature, there appears to be harmony amongst the uses of the word complexity in the academic literature. This harmony is evidenced by the emergence of three themes; multiplicity, relatedness, and difficulty of comprehension. However, difficulty of comprehension is an outcome of multiplicity and relatedness and hence, in the interest of creating a criterion free definition, will be omitted from this research. There also appears to be implicitly represented, consistent with systems theory (Boulding, 1956) and hierarchically nested systems (Simon, 1962), multiple levels where these dimensions are manifested; the portfolio, product, and component levels. Therefore, I propose the following definition of complexity.

*Complexity is the state of possessing a multiplicity of elements manifesting relatedness.*

Complexity in a product is manifested by both the multiplicity of, and relatedness among, elements contained within the product portfolio or the product itself. An element could be a component, subassembly, feature, design template, etc. Ceteris paribus, one product is considered more complex than another if it contains a greater number of elements or if elements are more interconnected than the other. I therefore define product complexity as follows:

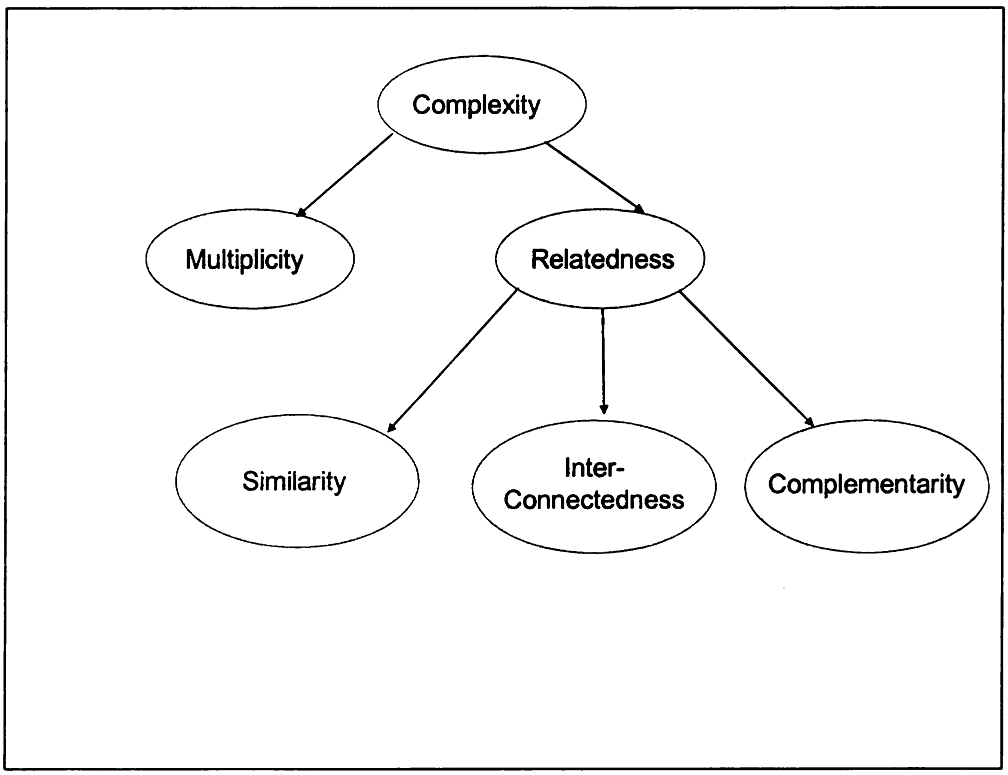
*Product complexity is a design state resulting from the multiplicity of, and relatedness among, product architectural elements.*

Applying this logic to product portfolios, reveals that the greater the combinatorial possibilities and degree of interconnection represented between items, the greater the complexity. As such, complexity in a product portfolio is defined as follows:

> *Product portfolio complexity is the state of possessing a multiplicity of, and relatedness among, products within the portfolio.*

Multiplicity relates to the enumeration of items. However, as can be seen in Figure 1, relatedness has three dimensions; similarity, interconnectedness, and complementarity. Similarity includes sharing technological characteristics such as part geometries or components, offering the same functionality, fulfilling the same strategic role in the portfolio as a prior product, or any other such indication of a like kind relationship. Interconnectedness relates to a connection via an interface such as those identified by Ulrich's (1995) slot, bus, and sectional typology. The gist is that there is a physical connection between two elements which may be mechanical or electrical. The interconnectedness of elements includes not only the physical connections, but also conceptual relationships. Thus two products in a portfolio may not be physically related, but rather related in a familial way. For example, a product that supplants another in the portfolio, the proverbial new and improved product, is connected to the old though the similarity of position in the portfolio, functionality offered, market segment targeted, or other logical connection. Complementary relatedness is used in the economic sense. The demand for one product influences that of another. The stronger this relationship, the more complimentary the products are. For example, computer servers and data storage devices are compliments as are mp3 players and digital music.

**Figure 1**
**Dimensions of Complexity**




It should be noted that in this study the term complexity is used in lieu of the term 'commonality'. There are many works which address commonality; however commonality is merely a descriptive term for one aspect of complexity. Specifically, commonality is a state of increased relatedness in conjunction with a state of decreased multiplicity. For example, when resistors of multiple tolerances are replaced with one resistor that has a tolerance consistent with the most stringent application. Because this resistor is used in more locations than before it replaced the others, it is more inter-related. There are more connections it has to differing parts of the product. The multiplicity is decreased because the total number of unique parts in the product has been reduced. Hence the conceptualization of product complexity presented herein subsumes commonality.

Within the context of this research, the focus is the portfolio of products. However, this research may offer insights to other levels e.g. subassemblies, modules, or components and in other contexts e.g. process steps or social systems.

### 1.4 Motivation

Prior research has shown that increased product complexity can be beneficial to efforts to increase sales revenue (Kekre & Srinivasan, 1990; Lancaster, 1979; Quelch & Kenny, 1994). However, the revenue increases at a diminishing rate and the increased costs associated with added complexity may eventually dominate the revenue gained (Baumol, Panzar, & Willig, 1982; Kotler, 1986; Lancaster, 1979; Moorthy, 1984; Quelch & Kenny, 1994; Robertson & Ulrich, 1998; Sievanen, Suomala, & Paranko, 2004). Thus the combination of diminishing sales returns and increasing costs due to complexity imply there is an optimal level of product portfolio complexity. Hence, finding and maintaining near optimal complexity levels is an implied, but difficult, management task. The task is difficult because the drivers of complexity have not been articulated, their impacts quantified, and the models and heuristics presented to date do not sufficiently capture the scope of the problem.

Researchers have addressed product complexity somewhat myopically, and often with the perspective that less complexity is always better. For example, some have suggested the inventory and risk pooling benefits from component commonality (Fisher et al., 1999; Hillier, 2000). Others have suggested that procurement cost reductions resulting from reducing part count (Meyer and Mugge (2001). Another research stream studies the influence of the product architecture on the firm's ability to communicate effectively and coordinate design activities (Galvin & Morkel, 2001; Meyer & Mugge, 2001; Sanchez & Mahoney, 1996; Ulrich & Tung, 1991). Yet another line of research relates to measures of research and development (R&D) effectiveness and the degree of modularity within a production process (Meyer, Tertzakian, & Utterback, 1997; Qiang, Mark, Ragu-Nathan, & Bhanu, 2004). Several studies examine the level of flexibility that various design architectures facilitate (Baldwin & Clark, 1997; Chang & Ward, 1995; Galvin & Morkel, 2001; Sanchez & Mahoney, 1996; Ulrich & Tung, 1991). Lastly, researchers have examined the effects of complexity on product development costs (Clark & Fujimoto, 1991). These studies identify design strategies including component standardization and reuse schemes, modular-based product architectures, and platform-based design approaches by which the operational costs of supplying a complex product portfolio can be reduced. These strategies enable inventory reductions, unit price acquisition curbs, redundancy of suppliers (Langlois & Robertson, 1992; Robertson & Langlois, 1995), and new schemas for organizing resources within the firm that can decrease cost (Meyer &

Mugge, 2001). However, the literature lacks studies that address the management of product portfolio complexity in a more comprehensive way.

The appropriateness and robustness of these strategies has not been rigorously examined empirically. Therefore, it is important to study complexity from a broader perspective to develop principles to apply in conjuction with other strategies. With market demands constantly driving toward more complexity and resource requirements suggesting less (Lawton, 2007; Patton, 2007), it is important that managers understand which strategies are effective for moving a business unit's product portfolio closer to profitable, if not optimal, levels of complexity.

The search for the right amount of complexity has spawned research that appears to reach contradictory conclusions. There is one body of literature which suggests that complexity reduction is desirable. There is another established body of literature that posits that firm performance is increased through more product complexity. The evidence provided by both camps is compelling. Thus there appears to be an unresolved gap in the literature in relation to complexity. This demonstrates the need to provide, from a theoretical basis, greater understanding of the advantages and disadvantages of the differing complexity dimensions.

In part, the lack of clarity is a result of an imprecise definition of complexity. For example, sometimes it seems that researchers are addressing the multiplicity dimension of complexity and sometimes the relatedness dimension. However, they speak in generic terms. This is problematic in that the ramifications of the two different types of complexity may be very different. Therefore an important first step in the reconceptualization is an improvement on the definition of complexity

This study provides a timely and first step toward improved clarity regarding complexity in that it investigates the relationship between product portfolio complexity, sales volume and cost. This is the first research to empirically assess how product complexity influences both sales volume and cost. It also addresses the gaps identified by Ramdas (2003), Krishnan and Ulrich (2001), and Yano and Dobson (1998). It does so by providing a theoretical base to explain the relationship between product complexity and cost and product complexity and sales volume by extending two well accepted theories; Performance Frontiers (Schmenner & Swink, 1998) and Transaction Cost Economics (Coase, 1937; Williamson, 1981, 1991, 1996, 2002).

**1.5 Form of research questions**

This dissertation develops and tests hypothesized relationships to address the following objectives:

- Identify and develop measures of the multiplicity and similarity dimensions of complexity that are predictive of various costs and volume effects.
- Test the relationship between the measures of complexity developed and various costs and sales volume.

- Determine the nature of the relationship between various dimensions of complexity and various costs and sales volume

To address these objectives, the study integrates the engineering, marketing, and operations management literatures to develop theoretical explanations for product complexity's impacts on the supply chain performance outcomes of cost and sales volume. The development of specific hypotheses are informed by past conceptual, analytical, and empirical research and are grounded in two well established theoretical frameworks. These hypotheses take the following general form:

- Complexity type X has a non-linear effect on supply chain non-recurring and recurring costs.
- The functional form of the relationship between complexity type X and resulting supply chain non-recurring and recurring costs Y will be nonlinear.
- Complexity type X has a positive and non-linear effect on sales volume

### 1.6 Overview of the research methodology

The data provided by a large designer and manufacturer of data processing equipment computer manufacturing firm includes financial statements, product configuration, and sales information for four brands. This data reflects quarterly activities for each brand for the most recent three years. The data set is organized as products nested within models nested within brands.

Fixed effect multiple regression models, time series regression, and panel data regression are used as appropriate to test the hypothesized relationships between sales or cost data and complexity factors.

### 1.7 Research Contribution

Little empirical work has been performed on the subject of product complexity (Bayus & Putsis, 1999; Lancaster, 1990; Ratchford, 1990) that can guide management practices. While studies investigating various complexity management strategies can provide some insight to the larger topic of product complexity e.g. Galvin and Morkel (2001), Meyer and Mugge (2001), Nobeoka and Cusumano (1997), Robertson and Ulrich (1998), and Sanchez and Mahoney (1996), they do not directly address or empirically validate relationships between product complexity and cost or sales volume. Nor do they, in any rigorous sense, provide explanations or quantifications of the conclusions proposed. None of these research studies provide theoretical explanations or identify specific metrics that are predictive of cost or sales volume.

Given the nature and focus of published research to date, there remains a gap. Research is needed to determine the optimal level of product complexity in the face of conflicting cost and revenue implications (Fisher, Iain, & MacDuffie, 1995; Fisher & Ittner, 1999). Fisher and Ittner (1999) go on to say that there is a general lack of understanding about the specific mechanisms through which complexity affects costs. Ramdas (2003) echoes this when she calls for research investigating the non-linear impact of complexity on cost.

Ishii, Jeungel, and Eubanks (1995) also corroborate the call for a need for greater understanding of how product complexity affects supply chain costs.

In light of these calls for additional insight, this study provides significant contributions to the research community. It provides a clear definition of complexity so that future research can more effectively build on the work of others and prior work can be reconceptualized thereby allowing the findings to be made more specific. This research establishes a sound theoretical framework by which complexity can be studied. This in conjunction with a more precise definition of complexity will facilitate an acceleration in advances on the topic. Additionally, this research will provide a theoretical basis that explains the functional forms of the relationship between different dimensions of complexity and various costs and sales volume. Maybe most significantly, this research will identify the functional relationship between complexity and sales volume and cost. Knowing the functional relationships of will enable managers to identify the optimal level of complexity in the portfolio to maximize either sales volume or profit.

### 1.8 Plan of Work

This research project follows the time table presented in Table 2.

**Table 2**
**Plan of Work**

| Activity | Target Completion Date |
|---|---|
| Frame research | January 1, 2007 |
| Draft dissertation topic proposal | September 15, 2007 |
| Defend dissertation topic | October 15, 2007 |
| Gather data | November 30, 2007 |
| Analyze data | February 29, 2008 |
| Synthesize findings | June 15, 2008 |
| Defend dissertation | July 15, 2008 |
| Final edits completed | July 31, 2008 |

## 2.0 Literature review

### 2.1 Introduction

The literature relating to product complexity is quite broad. It spans four major disciplines; marketing, engineering, operations, and organizations (Krishnan & Ulrich, 2001) and is informed by the mathematical and hard science literatures. Since the literature base is so wide, this review will address it relative to several focused areas. The areas that are pertinent include portions of the marketing, engineering, and operations management literatures relating to various aspects of product platforms, modularity, commonality, engineering design, portfolio theory, and product diversification.

The remainder of this chapter is organized as follows. First, a typology of product complexity is presented and the areas focused upon in this research are highlighted. Next, the current state of the pertinent literatures relating to product portfolio complexity is discussed. Last, there is a summation of the chapter.

### 2.2 Typology of Product Complexity

As defined prior, product complexity represents a multiplicity of related elements. Per the complex systems literature (Boulding, 1956; Simon, 1962) product portfolio complexity could be represented on several levels ranging from the portfolio of a firm's offerings down to the individual component level of the products within the portfolio. Complexity represented at the portfolio level is exemplified by the number of different models represented in the product portfolio (multiplicity) (Fisher et al., 1999). It is also represented by the rate of replacement (churn) of the products within the portfolio

(Ramdas, Fisher, & Ulrich, 2003). At the individual product level, which is addressed by Griffin (1997a) and Mac Cormick and Rusnick (2006), it is characterized as the number of features or functions embodied in a product (multiplicity) and their interconnectedness (relatedness). Lastly, there is complexity at the component level which has two dimensions; part count (Gupta & Krishnan, 1999) and interconnectedness (Tatikonda & Stock, 2003). For example, a product portfolio's complexity may be increased by increasing the total number of components it comprises (multiplicity) (Gupta & Krishnan, 1999), by increasing the number of technical functions (or "features") embodied in it (Griffin, 1997a), or by increasing the degree of interconnectedness among its constituent components, modules, or products (relatedness) (Tatikonda & Stock, 2003). Thus the typology contains four categories of complexity at each of three levels as shown in Figure 2. There is multiplicity complexity and three dimensions of relatedness complexity: similarity, interconnectedness, and complementarity. Each of these appear at each distinct level of complexity: portfolio, product, and component. This research will focus on multiplicity and similarity at the portfolio and product levels as depicted in Figure 3.

**Figure 2**
**Typology**

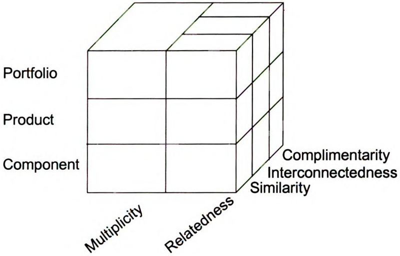
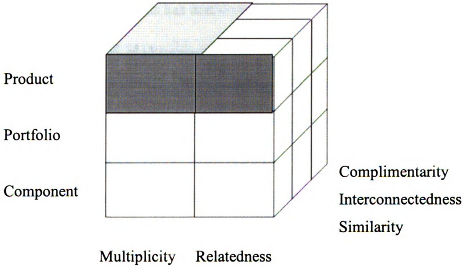



**Figure 3**
**Research Focus**



## 2.3 Portfolio Level Complexity

A portfolio of products represents the mix of products offered to the market, their stage of lifecycle, and competitive position (Day, 1977). It is one of the most strategic elements of the firm as it reflects resource allocation decisions e.g. decisions about which products and projects the firm should fund (Cooper, Edgett, & Kleinschmidt, 1997a). Applying the definition of complexity to the product portfolio yields the following insight. A portfolio that is complex will have a large number of products and / or the products within the portfolio will be highly related in some way. Therefore the decisions about additions, deletions, and the inter-relationships among the products within the portfolio are of strategic importance.

Decisions about products entering, exiting, and replacing others within the portfolio are made with two objectives in mind; balancing the funding requirements of the firm and risk mitigation (Cooper et al., 1997a; Henderson, 1970, 1972a, 1972b). Firms seek a portfolio that can both generate large amounts of cash currently and offer significant long term sales growth potential. This has traditionally been accomplished by satisfying as many customer preferences as possible with the ultimate goal being the creation of the ideal product for each segment (Dobson & Kalish, 1988). Within this context firms seek to minimize risk from exposures to threats such as economic events, political or regulatory vagaries, or supply disruption (Day, 1977). However this leads to a revenue / sales volume focus and a failure to take into account the requirements of providing the product to the customer. The result is a one sided analysis with a reduction in profit as a potential outcome.

Portfolio theory (Markowitz, 1959) emerged as a means to model and quantify the risks within a portfolio of products. As such, it provides a theoretical basis for the forces driving product portfolio complexity. Portfolio theory suggests that products can be treated as investments; each yielding a unique revenue / sales volume stream subject to volatility. The objective is to minimize the variability of financial returns (risk) or maximize the return for a given level of risk. The latter forms an efficient frontier of project investment (Cardozo & Smith, 1983). One means by which risk can be mitigated is the assembly of a portfolio containing products exposed to different market segments, geographies, etc. Historically, this has meant providing a product tailored to each of these niches. However, once the portfolio is large enough there are no longer benefits to adding more items since the average rate of return will tend to the true mean and adding one more cash flow stream will not significantly change it. Also, the efficient frontier hints at the existence of a correct or optimal configuration. Hence, diversification beyond a certain point may not be advantageous.

The genesis of product complexity resides within the portfolio level. The twin objectives of funding requirements (generating large amounts of cash currently and long term sales growth potential) and risk mitigation (Henderson, 1970, 1972a, 1972b) are powerful forces driving added levels of complexity. Firms are pressured to introduce product variants into additional markets to offset economic or political risks as well as offer broader lines in the hope of increasing the chance of a runaway success. There are further forces such as competitive positioning and responses, reward structures, organizational structure, data management maturity, and governance that work to cause firms to offer more products (Closs, Jacobs, Swink, & Webb, 2007). These forces potentially have costly ramifications including increases in the costs of production, inventory, warranty, shipping, development, administrative support, marketing, and financing.

Peter Drucker (1963b) observed the difficulty domestic firms were having competing in global markets and hypothesized that the market performance of the products of U. S. firms was hindered by portfolios that were too broad. Specifically, he proposed that focusing on fewer products would enhance competitive strength. Drucker's work spawned several approaches to finding the mix of products to hold in the portfolio that maximized revenue / sales volume and growth opportunities. Several approaches were proffered e.g. Wright (1978), Allen (1979), Wind (1975), but the one gaining the most widespread adoption and attention was the cash flow matrix from the Boston Consulting Group (Henderson, 1970).

The solution presented by Drucker (1963b), when viewed in the context of portfolio theory, essentially suggests a shifting of the position of the portfolio along the risk / return frontier. By reducing the scope of the portfolio, returns can be increased, but at the expense of added volatility. This led to two questions: is there a way to garner the gains from reduced portfolio scope yet not relent on the drive to increase revenue / sales volume, and how can the problem be modeled to gain greater insight. The complexity management strategies of standardization, product platforms, and modularity are the answers that have been offered so far to the first question.

The first of these three complexity management strategies to be investigated was standardization; the use of common components (Evans, 1963; Lee & Tang, 1997). The first significant research into this strategy was the operationalization of the construct (Collier, 1981). Researchers used this and measures developed in subsequent articles (Martin & Ishii, 1997; Wacker & Treleven, 1986) to ascertain the benefits of increased standardization. Unfortunately, the research focused upon inventory costs and availability almost exclusively, although this aspect of the topic is extensively covered by many researchers e.g. (Baker, Magazine, & Nuttle, 1986; Collier, 1982; Farrell & Simpson, 2003; Fisher et al., 1999; Fisher & Ittner, 1999; Hillier, 2002; McClain, Maxwell, Muckstadt, Thomas, Weiss, & Collier, 1984; Rutenberg, 1971; Swink & Closs, 2006). This leaves open the need to investigate total cost implications.

The revenue impacts of too much customer perceived standardization were researched empirically by Kim and Chhajed (2000) and analytically by Desai, Kekre, Radhakrishnan, and Srinivasan (2001). They report that high levels of perceived standardization can influence the price, or the consumer's perception of value, by putting downward price pressure on the high price product and upward price pressure on the low price product. However, remaining to be researched are implications of other types or measures of portfolio complexity.

Product platforms were the next complexity management strategy to be explored. The product platform is presented as a means to migrate products from one quadrant of the BCG matrix to another (Meyer & Lehnerd, 1997; Sanderson & Uzumeri, 1995) and thus improve the quality of the portfolio as related to revenue / sales volume growth and risk mitigation. In particular, the implied objective is to maximize the number of stars given the funding available from the cash cows. The platform enables the entry into new markets (the chance to create new stars) while facilitating cash cows through scale economies (Farrell & Simpson, 2003; Krishnan, Singh, & Tirupati, 1999; Sanderson & Uzumeri, 1995).

There appear to be limits however to the benefits that can accrue from a complexity management strategy entailing platforms. Krishnan and Gupta (2001) found limits to the benefits from platforms that were brought about by increased component costs attributable to standardization and design costs. They found that increased standardization was beneficial as long as the unit cost of the component being standardized was not too high relative to alternative suitable components (multiplicity). This leads to the conclusion that there is a diminishing benefit to reducing product complexity. Similar findings are reported in the engineering literature where product performance is used as the guide to finding the ideal number of platforms to deploy across a product portfolio (Nelson, Parkinson, & Papalambros, 2001; Seepersad, Mistree, & Allen, 2002; Simpson, Seepersad, & Mistree, 2001b). Since the consensus is that a portfolio of higher performing products entails a greater number of components, this is effectively an investigation into the tradeoffs between the complexity dimensions of similarity and multiplicity. Again, the pattern of diminishing returns to decreasing complexity is expected. Thus, one interpretation of these findings is that a level of complexity in the portfolio greater than the theoretical minimum is requisite because it is not economical to standardize on one platform.

A different group of researchers (Farrell & Simpson, 2003; Krishnan et al., 1999; Meyer & Lehnerd, 1997; Sanderson & Uzumeri, 1995) contend that platforms can be advantageous to cost effectively pursuing additional market segments. Thus it would appear there are increasing returns to decreasing complexity. This finding is not necessarily paradoxical to that of Krishnan and Gupta (2001). A more likely conclusion is that the benefit realized from reducing levels of product complexity may be concave.

Modularity is another complexity management strategy that has been explored in the literature. Modularity emphasizes minimization of strong interdependencies within a product (Baldwin & Clark, 1997, 1999). Modularity is a systems concept that defines the degree to which elements can be combined to create a wide variety of end items (Evans, 1963; Lampel & Mintzberg, 1996; Pine, Victor, & Boynton, 1993; Schilling, 2000; Ulrich, 1995; Walz, 1980). Thus, like product platforms, modularity is proposed to be a means by which a broad product portfolio can be offered. Also like product platforms, there is research revealing both beneficial and detrimental outcomes to its use. The benefits include economies of scale (Pine et al., 1993), inventory reductions (Fisher et al., 1999; Kim & Chhajed, 2000; Meyer & Mugge, 2001; Mirchandani & Mishra, 2002; Ramdas & Randall, 2004; Swink & Closs, 2006; Tu, Vonderembse, Ragu-Nathan, &

Ragu-Nathan, 2004), engineering efficiencies (Collier, 1981), and improved coordination (Danese & Romano, 2004; Galvin & Morkel, 2001; Nobeoka & Cusumano, 1997; Sanchez & Mahoney, 1996; Schilling, 2000). However, the benefits are a function of the cost of the components being standardized (Fisher & Ittner, 1999; Karmarkar & Kubat, 1987; Ramdas et al., 2003).

Along with efforts to find effective strategies to manage the impacts of complexity is a stream that uses mathematical modeling to find the ideal portfolio composition. The modeling approach was initially pursued by researchers who were concerned that the cash flow techniques offered by consultants suffered from substantial amounts of subjectivity. This led to the attempt to model the problem analytically e.g. Green and Krieger (1985), McBride and Zufryden (1988) or Dobson and Kalish (1988) or through optimization techniques e.g. Archer & Ghasemzadeh (1998; 1999), Baker (1974), Baker & Pound (1964), Danila (1989), Ghasemzadeh & Archer (2000), and Liberatore (1988). Unfortunately none of these models were put to the test for feasibility (Cooper et al., 1997a).

There are limitations to pursuing mathematical models. The analytical models such as those reported by Green and Krieger (1985), McBride and Zufryden (1988) or Dobson and Kalish (1988) are limited by several assumptions. The analytical models assume there is only one product considered with one attribute of interest to the consumer, the customer always prefers more than less, the segments are ordered the same at every level of the attribute under consideration, and there is no cost of production (Dobson & Kalish, 1988). The extensive assumptions are required due to the extremely high levels of difficulty in solving problems with unconstrained and unstable boundaries. More recent literature (Dobson & Kalish, 1993; Nair, Thakur, & Wen, 1995) has focused on numerical models and heuristics. For example, Rao, Swaminathan and Zhang (2004) use an optimization approach to study certain aspects of product complexity. In their research they model and develop heuristics for the effect of demand variance and benefits of substitution on inventory levels and production set ups. However, these too did not consider production costs and therefore may lead to untenable solutions.

In conjunction with the portfolio of products represented at the firm or brand level, there is a related portfolio; the portfolio of projects under development that may enter the product portfolio. Scholars (Dean & Nishry, 1965; Moore & Baker, 1969; Bonini, 1975; Utterback & Abernathy, 1975) began to address this level shortly after Drucker's (1963a) article appeared. Several researchers have made the attempt to model the problem analytically or through optimization techniques (Archer & Ghasemzadeh, 1998; Archer & Ghasemzadeh, 1999; Baker, 1974; Baker & Pound, 1964; Danila, 1989; Ghasemzadeh & Archer, 2000; Liberatore, 1988). Unfortunately none of these models were put to the test for feasibility (Cooper et al., 1997a). This could possibly be due to the fact that interrelationships between new and existing products are very difficult to quantify (Cooper, Edgett, & Kleinschmidt, 1997b). The lack of practical value to the analytical and optimization approaches is demonstrated by a lack of both use and interest among the firms represented in a review of 205 major U.S. firms (Cooper et al., 1997b; Cooper, Edgett, & Kleinschmidt, 1999). However, managers of these firms did express interest in decision tools and rules of thumb to guide decisions about which products should enter, exit, or remain in the portfolio (Cooper, Edgett, & Kleinschmidt, 2001).

Product platforms, modularity, and standardization are all strategies to manage the level of product and component level complexity (Choi & Krause, 2006). Using the example of the bicycle industry Galvin and Morkel (2001) present a case for the benefits of standardization. Since interfaces are standardized in the bicycle industry, a manufacturer that cannot obtain a supply of sprockets from company X can easily secure the product from company Y. The result is that supply disruptions are minimized and the price of sprockets is kept low. This illustrates the power of standardized interfaces. Standardized interfaces enable inventory reduction, unit price acquisition curbs, and redundancy of suppliers enabling a decrease in supply interruption risks. The result is affordable high quality products that are widely and readily available (Langlois & Robertson, 1992; Robertson & Langlois, 1995). Thus there appear to be significant benefits to increasing the similarity represented within a product or portfolio of products.

The literature also presents examples of benefits resulting from reduced multiplicity. One is the leveraging of a product platform across the product line (Meyer & Mugge, 2001). The result is new schemas for organizing resources within the firm that can increase effectiveness and decrease costs. Several other researchers explore the relationship between multiplicity and inventory (Collier, 1982; Fisher et al., 1999; Fisher & Ittner, 1999; Ramdas et al., 2003) and find that reduced multiplicity leads to lower inventory costs and better service levels. Ramdas and Randall (2004) report that reduced multiplicity leads to improved quality. Thus benefits to reducing product multiplicity appear to be well established.

However, research has shown that product complexity can increase sales revenue (Kekre & Srinivasan, 1990; Lancaster, 1979; Quelch & Kenny, 1994; Sanderson & Uzumeri, 1995). Revenue / sales volume will grow incrementally for each variant because each variant can be targeted at an untapped niche. Thus the marketing literature has established the benefit to the firm of increased levels of portfolio complexity. While it is desirable to grow revenue or sales volume, some have postulated that the costs associated with increased product complexity resulting from additional variants will eventually overcome the benefit from increased revenue or sales volume (Kotler, 1986; Sievanen et al., 2004; Suomala, Sievanen, & Paranko, 2004); the result being a concave profit function (Lancaster, 1990). However, unknown is the precise shape of this curve. One group of researchers has begun to address this question, but have yet to go beyond exploratory research hypothesizing that the kurtosis and skewness of the curve will vary by industry and over time (Closs et al., 2007). Closs et al. (2007) and Lancaster (1990) imply that product complexity greater than the theoretical minimum may be beneficial.

Yano and Dobson (1998) report that the effect of product complexity on profit has seldom been considered. Similarly, few industries have developed effective analytical tools to manage both the revenue or sales volume from variety and the countervailing costs simultaneously in product portfolio decision making (Otto, Tang, & Seering, 2003). These analytical tools should account for the scope economies recognized from multiple customer and market segments and the reduction of scale economies in designing and delivering the product (Yano & Dobson, 1998).

Ramdas (2003) states that the prescriptive models for product variety, presented in the literature, often have limited use due to a focus on narrow tradeoffs within functional silos which ignore important interdependencies. She adds that simply adding terms to existing models will not remedy this problem. Developing practical models will require understanding (and quantifying) the underlying factors that intertwine different functions, such as product architecture (Krishnan & Ulrich, 2001).

Since the literature characterizes as beneficial both increases and decreases in complexity, there is a need to reconceptualize the apparent paradox (Van de Ven, 1989). This is implicitly supported by Gershenson (2003) who finds a need to illuminate this topic and hence calls for studies to validate the benefits of complexity management strategies such as modularity. Qiang, Mark, Ragu-Nathan, and Bhanu (2004) further add that identifying new theory in this area is growing in importance. An example of this need is found in the work of Randall and Ulrich (2001) who show that complexity is related to differing supply chain outcomes. However, they do not offer a means to quantify the relationship and thus cannot make predictions. This points to the need to conduct theory building research that can provide a more complete understanding of the topic.

**Table 3**
**Summary of Literature**

| Author | Journal | Year | Title | Findings |
|---|---|---|---|---|
| Choi & Krause | Journal of Operations Management | 2006 | The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation | Platforms, modularity and standardization are all strategies to manage product / portfolio complexity |
| Closs, Jacobs, Swink & Webb | Journal of Operations Management | 2007 | Toward a theory of competencies for the management of product complexity: Six case studies | Multiple forces such as competitive positioning, IS maturity, and governance combine to impact the number of products offered |
| Collier | Decision Sciences | 1981 | The Measurement and Operating Benefits of Component Part Commonality | Presented a metric to quantify the degree of commonality |
| Collier | Management Science | 1982 | Aggregate safety stock levels and component commonality | Safety stock diminishes with an increased level of commonality index |
| Conner, De Kroon & Mistree | ASME Design Engineering technical Conference | 1999 | A product variety tradeoff evaluation method for a family of cordless drill transmissions | A method is presented to evaluate the tradeoff between commonality and an individual product's performance |
| Desai, Radhakrishnan, & Srinivasan | Management Science | 2001 | Product differentiation and commonality in design: Balancing revenue and cost drivers | Excessive customer perceived commonality influences price |
| Dobson & Kalish | Management Science | 1993 | Heuristics for pricing and positioning a product-line | Feature proliferation arises through drive to satisfy as many customer preferences as possible |
| Du, Jaio & Tseng | Concurrent Engineering: Research and Application | 2001 | Architecture of Product Family: Fundamentals and Methodology | Introduce a measure of variety of choice at the product family level |
| Farrell & Simpsom | Journal of Intelligent Manufacturing | 2003 | Product platform design to improve commonality in custom products | Provides a procedural approach to determining the optimal number of platforms |

**Table 3**
**Continued**

| | | | | |
|---|---|---|---|---|
| Fellini, Kokkolaras & Papalambros | Journal of Mechanical Design | 2006 | Platform selection under performance bounds in optimal design of product families | A model is presented to generate the optimal number of products to offer the market subject to performance bounds |
| Fisher, Ramdas & Ulrich | MS | 1999 | Component sharing in the management of variety: A study of automotive breaking systems | Sharing of components is largely a factor of volume. Lower volumes result in greater sharing. |
| Fixson | JOM | 2005 | Product architecture assessment: a tool to link product, process, and supply chain design decisions | Presented a means to operationalize 'connectedness' |
| Gerchak & He | IIE Transactions | 2003 | On the benefits of risk pooling and the variability of demand | Increased demand variability increases the risk pooling benefits of commonality in most circumstances |
| Gerchak, Magazine & Gamble | Management Science | 1988 | Component commonality with service level requirements | Deploying commonality is beneficial to maintaining service levels |
| Henderson | Perspectives | 1970 | The product portfolio | Product variants are introduced to offset economic risks |
| Hillier | Naval Research Logistics | 1999 | Component commonality in multi-period assemble to order systems | Commonizing more expensive parts isn't always recommended in multi-period cases |
| Hillier | IIE Transactions | 2000 | Component commonality in multi-period assemble to order systems | Commonizing more expensive parts isn't always recommended in multi-period cases |
| Jiao & Tseng | Journal of Intelligent Manufacturing | 1999 | A methodology of developing product family architecture for mass customization | Provides a model based approach to developing a product family architecture. This PFA can be leveraged for commonality |
| Jiao & Tseng | Journal of Engineering Design | 2000 | Understanding product family for mass customization by developing commonality indices | Proposes a commonality measure |

**Table 3**
**Continued**

| | | | | |
|---|---|---|---|---|
| Kaski & Heikkila | International Journal of Technology Management | 2002 | Measuring product structures to improve demand-supply chain efficiency | Develops a dependency index that can be used to determine the strength of relationships between modules |
| Kim & Chhajed | European Journal of Operational Research | 2000 | Commonality in product design: Cost saving, valuation change and cannibalization | Excessive customer perceived commonality influences price |
| Kota, Sethuraman & Miller | Journal of Mechanical Design | 2000 | A metric for evaluating design commonality in product families | Presented a metric to operationalize commonality |
| Krishnan & Gupta | Management Science | 2001 | Appropriateness and impact of platform-based product development | There a limits to the benefits of platforms imposed by the cost of components |
| Kumar | International Journal of Flexible Manufacturing Systems | 2005 | Mass customization: Metrics and modularity | Introduces metrics that quantify the degree of customization |
| Lancaster | Marketing Science | 1990 | The economics of product variety: A survey | Increased product complexity increases sales revenue |
| Lin, Breitwieser, Cheng, Eagan, & Ettl | International Journal of Flexible Manufacturing Systems | 2000 | Product hardware complexity and its impact on inventory and customer on time delivery | Feature substitution is acceptable if costs are equivilent. Eliminating features for which there is low demand is superior to elimination of features for which there is a low usage |
| MacCormick & Rusnak | POMS conference | 2006 | Exploring the Relationship Between Product Architecture and Organizational Form: A Test of "Conway's Law" | Presented an approach to calculate 'connectedness' |
| Martin & Iishi | ASME Design Engineering technical Conference | 1997 | Design for variety: Development of complexity indices and design charts | Offers a method to quantify process commonality |

**Table 3**
**Continued**

| | | | | |
|---|---|---|---|---|
| Martin & Iishi | Research in Engineering Design | 2002 | Design for variety: developing standardized and modularized product platform architectures | Presented several metrics for operationalizing commonality |
| Mikkola | The Journal of Product Innovation Management | 2006 | Capturing the Degree of Modularity Embedded in Product Architectures | This paper introduces a mathematical model, termed the modularization function, for analyzing the degree of modularity in a given product architecture. |
| Mikkola & Gassman | IEEE Transactions on Engineering Management | 2003 | Managing Modularity of Product Architectures: Toward an Integrated Theory | This paper introduces a mathematical model, termed the modularization function, for analyzing the degree of modularity in a given product architecture. |
| Nelson & Parkinson & Papalambros | Journal of Mechanical Design | 2001 | Multicriteria optimization in product platform design | A nonlinear optimization model is presented to generate the optimal number of products to offer the market based upon performance characteristics\ |
| Novak & Eppinger | Management Science | 2001 | Sourcing by design: Product complexity and the supply chain | Vertical integration of production and complexity of design are complements |
| Ramdas | Production and Operations Management | 2003 | Managing product variety: An integrative review and research directions | Prescriptive models in the literature addressing portfolio variety focus on narrow tradeoffs and ignore important interdependencies limiting their usefulness |
| Ramdas, Fisher & Ulrich | MSOM | 2003 | Managing variety fo assembled products: Modeling component systems sharing | Presents a linear program formulation to guide the determination of components to commonize. Reduced multiplicity leads to less inventory and better service levels |

**Table 3**
**Continued**

| | | | | |
|---|---|---|---|---|
| Randall & Ulrich | MSOM | 2001 | Product variety, supply chain structure, and firm performance: Analysis of the US bicycle industry | Established the relationship between supply chain structure and product complexity |
| Rao, Swaminathan & Zhang | IIE Transactions | 2004 | Multproduct inventory planning with downward substitution, stochastic demand and setup costs | With nonzero setup costs, optimal inventory levels may increase with component standardization |
| Roque | Midwest DSI conference | 1977 | Production-inventory systems economy using a component standardization factor | Presented several metrics for operationalizing commonality |
| Salvador, Forza & Rungtusanatham | Journal of Operations Management | 2002 | Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions | Proposes two types of modularity - combinitorial & component swapping - that can reduce impact of variety on operations |
| Sanderson & Uzumeri | Research Policy | 1995 | Managing Product Families - The Case Of The Sony-Walkman | Platforms can be leveraged into additional niches to generate revenue growth |
| Seepersad, Mistree & Allen | ASME Design Engineering technical Conference | 2002 | A quantitiative approach for designing multiple platforms for an evolving portfolio of products | Relates the result of using a goal programming technique to determine the ideal number of platforms for a family |
| Sievenan, Suomala & Paranko | Industrial Marketing Management | 2004 | Product profitability: Causes and effects | Costs of adding items to the portfolio will eventually subsume the revenue gains from the addition |
| Simpson & D'Souza | Concurrent Engineering: Research and Application | 2004 | Assessing variable levels of platform commonality within a product family using multiobjective genetic algorithm | Suggests the use of deviation functions to measure the level of commonality across a product family |

**Table 3**
**Continued**

| | | | | |
|---|---|---|---|---|
| Simpson, Conner & Mistree | Concurrent Engineering: Research and Application | 2001 | Balancing commonality and performance within the concurrent design of multiple products in a product family | Developed a non-commonality and performance deviation index to quantify the tradeoff between commonality and performance |
| Thevenot, Nanda & Simpson | ASME Design Engineering technical Conference | 2005 | A methodology to support product family redesign using a genetic algorithm and commonality indices | Introduces the use of a genetic algorithm using shape and assembly factors from the product to determine the optimal degree of commonality |
| Thonemann & Brandeau | Operations Research | 2000 | Optimal commonality in component design | Develop a linear program to determine the optimal level of component commonality |
| Wacker & Treleven | JOM | 1986 | Component part standardization: an analysis of commonality sources and indices | Presented several metrics for operationalizing commonality |

### 2.4 Summary

In summary, topics related to product portfolio complexity management have been active in the literature since the late 1950's. However, the bulk of the literature pertaining to product complexity, no matter the level of analysis (portfolio, product, component), is focused narrowly on inventory effects. Even the research creating measures of complexity is done so with the intent of using the measures to gain insight to inventory effects. There has been a small amount of research in the engineering literature investigating the impact of complexity on product performance and development project timing. When viewed retrospectively through the lens of product complexity, each work addresses only a portion of the topic, e.g. considering revenue in isolation of cost. My contention is that the underlying dimensions of interest are multiplicity and relatedness and that, although admirable, prior research has failed to simultaneously address these underlying dimensions. This has prevented the development of robust theory that can guide both research and application. Pervasive in the literature is the tacit acknowledgement that there is an optimal level of complexity e.g. portfolio breadth, market diversity, etc., but the research most always approaches the topic from the perspective that less is better.

There are clear gaps that become apparent from the literature review. First is the need to improve the definition of complexity since the existing research lacks clarity due to inconsistent meanings. Second is the need for heuristics addressing production costs since current ones consider revenue or market share in isolation (Dobson & Kalish, 1993; Nair et al., 1995). The models published to date are limited by assumptions: one product considered with one attribute of interest to the consumer; the customer always prefers more than less; the segments are ordered the same at every level of the attribute under consideration; and there is no cost of production (Dobson & Kalish, 1988). These assumptions are due to the extremely high levels of difficulty in solving problems with unconstrained and unstable boundaries. Empirical research into complexity management strategies has shown there are relationships between product complexity and the competitive priorities of cost, quality, flexibility, and delivery (Jacobs, Droge, Vickery, & Calantone, 2006; Jacobs, Vickery, & Droge, 2007). However, it does not provide insight into the functional nature of and relationships between the various dimensions of complexity as they pertain to competitive performance.

## 3.0 Theory Development

There are two theoretical perspectives that provide insights regarding the effect of product portfolio complexity has on sales volume and cost. Both perspectives offer a predictive element, in a directional sense, as well as some rationale for the predicted outcome. These two perspectives are the Theory of Performance Frontiers (Clark, 1996; Hayes & Pisano, 1996; Schmenner & Swink, 1998; Skinner, 1996) and Transaction Cost Economics (TCE) (Coase, 1937; Williamson, 1981, 1991, 1996, 2002).

## 3.1 Two Theories

### 3.11 Theory of Performance Frontiers

The Theory of Performance Frontiers (TPF) is based in the neoclassical school of economics, which holds that economic growth arises from technological progress and output can be represented by a production function (Meade, 1962). Several economists built upon this foundation to establish that there is a diminishing return to investments, and that substitutions of resources were possible which could positively impact productivity (Keynes, 1936; Leontif, 1941; Pareto, 1906; von Bohm-Bawerk, 1889). Thus there is a limit to the performance an organization can achieve given a chosen set of assets. Schmenner and Swink (1998) refer to this limit as the "asset frontier." There is a second performance limit, interior to the asset frontier, determined by the policies and procedures of the organization, called the "operating frontier" (Schmenner & Swink, 1998). The theory states that an organization may move its operating frontier closer to the asset frontier by revising the organization's policies and procedures in ways that more fully utilize its assets. The resulting increased effectiveness should be reflected in gains in productivity and financial performance (Clark, 1996; Hayes & Pisano, 1996; Schmenner & Swink, 1998; Skinner, 1996). However, this gain is nonlinear. The gain increasingly diminishes as the operating frontier approaches the asset frontier. Similarly the cost to move the operating and asset frontiers closer together grows exponentially as the gap is narrowed (Schmenner & Swink, 1998). Putting the relationship between the asset and operating frontiers into the context of product complexity, TPF suggests that product designs, which are intangible assets of the firm, will be reused as often as is practical given the assumption that the designer deems the existing design to be compatible with the objectives of the new development project. Reusing a design is the equivalent of moving the operating frontier closer to the asset frontier, as it enables a fuller utilization of the organization's assets. TPF implies that better financial performance will result when assets are better utilized; hence better performance from design reuse. Design reuse is manifested by the reuse of components, assemblies, and systems. Taken a step further, TPF may predict the use of modular architectures as this architectural form may offer the greatest opportunity for asset utilization. Modularity enables increased utilization of the intangible design assets and additional hard and soft assets in the supply chain that are dependent upon design. For example, product support personnel can be more productive in the field because problems are easier to diagnose and resolve (Karmarkar & Kubat, 1987) fewer unique problems are expected and entire modules can be interchanged rather than repaired at the customer site. Also, equipment to produce the modules may be more fully utilized due to the ability to build modules to stock and assemble them in configurations consistent with customer demand (Feitzinger & Lee, 1997; Pine et al., 1993; Worren, Moore, & Cardona, 2002).

Theory of Performance Frontiers and the similarity dimension of complexity are related in the following way. First, consider the case where the production equipment is the asset. For example, a lathe is an asset of the firm. It seems evident that a more fully utilized lathe builds more products and thus scale benefits are recognized. Hence unit cost can reach its theoretical minimum. There are clearly exceptions to this case, such as labor that becomes increasingly more expensive the longer the lathe produces products, thus it should not be construed here as a universal law, but rather as an effect seen generally.

Further developing the example of the lathe, consider that the lathe supports two products and that each time production calls for a change in products, a set up is incurred. This set up consumes some percentage of the total available productive time of the equipment. The result is that a structural element arises, represented by the gap between the operating and asset frontiers. Hence the operating frontier can never reach the asset frontier. Therefore maximum performance can never be attained. This scenario is replicated throughout production facilities hundreds of times as the numbers of tools and other productive assets increases, and the number of unique products to be produced upon them increases. This fact leads to the realization that multiple dissimilar products lead to multiple unique or uniquely configured production assets whereas multiple products sharing design characteristics tend to result in increased utilization of fewer unique assets. Thus moving the operating frontier closer to the asset frontier by designing additional products with similar geometries leads to improved financial performance and increasing the number of separate products tends to push the operating frontier away from the asset frontier with the result being diminished financial performance.

The diminished financial performance is reflected in two ways. First, it may be reflected in the decrease in the sales volume theoretically possible. The proverbial lathe spends a certain amount of time inactive, and thus not providing parts for sale. Second, the time spent setting up must be paid for. An employee is thus earning wages for performing non-revenue generating work. This cost is then amortized over the products produced with the effect of increasing the per unit transformation cost relative to the fully utilized scenario.

Granted, there is no consideration of the value of the products produced, and assumptions include hourly pay not piece work, and the ability to sell everything manufactured. These assumptions and simplifications are consistent with traditional assumptions of economics and they enable the revelation of the primary principle; the similarity dimension of complexity has significant operational impacts which lead to certain sales volume and cost implications.

Now consider the case where product designs are assets of the firm. They are included within the asset class of intangibles and intellectual property and represent the irreversible work of engineers and other technical professionals. This labor creates the product design which is represented by an asset frontier; there is only so much benefit that can be realized from that design and it is constrained by the very nature and quantity of the labor that created it. If a product design is used once and then abandoned, there is a given amount of benefit the organization will recognize. However, if the design can be used a second time (i.e. for a second product) then greater benefit is anticipated. Thus the reuse of the design increases the utilization of the design. Hence the operating frontier has moved closer to the asset frontier; the benefit being primarily recognized as decreased engineering expense and possibly decreased tooling costs and increased scale economies.

Theory of Performance Frontiers predicts that complexity in the relatedness dimension will lead to better cost outcomes. This occurs through the enhanced utilization of existing resources; both tangible and intangible. However, the benefits will increasingly diminish with ever greater levels of relatedness.

### 3.12 Transaction Cost Economics

Transaction Cost Economics is generally used to explain the governance of firms and why they choose certain business transactions over others. Williamson (1991) indicates that TCE is also useful for explaining organizational structures within a firm. If a product portfolio is taken to posses a given structure, then it is appropriate to apply TCE to explain the structure of a portfolio of products. The premise of TCE is that organizations will act to minimize costs. These costs include both out of pocket expenses and costs associated with risk. The three risks that TCE identifies are asset specificity, environment, and opportunism.

There are a variety of out of pocket costs that will increase with increasing levels of product portfolio complexity. Examples include marketing and advertising costs. These will increase with both total number of products and with increased rates of replacement due to the design and execution of additional marketing campaigns. The additional campaigns result in increased advertising and accompanying increases in media buys, promotional materials, and sales training. The extra number of products, both new and replacement, require a higher level of managerial oversight to coordinate the various sales and marketing campaigns, delivery channels, and other aspects of the business. The result is an increase in cost. Beyond the sales and marketing impacts there are cost ramifications deeper within the organization. These include increases in the areas of manufacturing operations and product development.

Learning curve theory provides insight to the mechanisms that cause increases in cost with increased numbers of transactions. For example, within manufacturing operations, out of pocket costs increase because a larger number of separate items results in less experience with any given item. Learning curve theory indicates that the number of defects will be higher and productivity lower because the process is not as far down the experience curve (Wright, 1936). These defects will result in the out of pocket costs of scrap or rework.

Another manner by which increasing the number of transactions increases cost can be seen in the effects on inventory. Assuming the total demand is constant, increasing the number of products makes forecasting more difficult due to a relative increase in demand variability across products (Bendoly, Blocher, Bretthauer, & Venkataramanan, 2007; Caplin, 1985). Inventory theory indicates that to maintain a consistent service level in the presence of increased variability, the amount of available inventory must increase (Mize, White, & Brooks, 1971). This impairs short term cash flow and raises financing costs. Additionally, procurement costs might increase as a greater number of requisitions must be processed.

Within the product development organization, there are additional non-recurring costs incurred from the added design, certification, qualification, and related efforts that arise from additional products or those that are more robust. Thus TCE predicts that an increase in portfolio complexity will negatively impact out of pocket cost.

TCE holds that there are costs associated with certain kinds of risk. The first of these is asset specificity. If the product design is considered to be the asset then the more finely focused a niche at which the product is targeted, and the more the product is the only asset satisfying the demand from that particular niche, the more specific that asset has become. Thus TCE predicts that increased complexity in the multiplicity dimension will increase asset specificity and its attendant costs. In contrast, the relatedness dimension of complexity will work to decrease asset specificity. Products are related when designs are re-used e.g. shared platforms or modules. Design reuse reduces the number of engineering hours incurred to design a product (Monteverde and Teece (1982) use engineering hours as a proxy for asset specificity). Some have argued that engineering hours is a poor proxy (Ulrich, Sartorius, Pearson, & Jakiela, 1993), but it is clearly an indication of firm resources being dedicated to a specific task. Furthermore, once spent, these hours cannot be recovered. There is only one means by which the specificity can be mitigated and that is to reuse the design. The reuse of the design constitutes a reduction in asset specificity since the underlying asset (engineering hours) is no longer tied to a single revenue / volume stream (product), but is distributed across two or more. Thus, the risk (and accompanying costs) of asset specificity is increased with increasing levels of multiplicity, but decreased with increasing levels of relatedness.

The second risk category addressed by TCE is that of environmental uncertainty. Environmental uncertainty includes such things as the vagaries of markets, and competitive responses to a product introduction. It also includes the environment within the firm thereby capturing such things as quality, equipment performance, and the capabilities of personnel. Environmental uncertainty will be impacted by complexity differently depending on the dimension of complexity. For example, an increase in the number of dissimilar products exposes the firm to higher levels of uncertainty and hence cost. These costs are manifested in a variety of ways. One such example is poorer quality attributable to lack of experience with a product. Additionally, equipment may be stressed by an increase in the variety of parts processed; the increase in variety leading to additional setups that impair the productivity and ultimately impact the ability to schedule maintenance. Alternatively, complexity in the relatedness dimension will have a beneficial impact on uncertainty and the accompanying costs. There are several reasons for this which can be seen from the example of design reuse. Reusing a design reduces environmental risk because the cost, quality, and demand history are known to a greater degree for the existing design than that of a new design. There are potentially fewer problems that will arise in the transfer from the design team to the manufacturing group and the quality level is understood and should continue to improve due to learning curve effects. This leads to a reduction in the risks of recall or product failure in the market. Forecasts can be more accurate, which translates to greater product availability and hence improved delivery performance. The risk of purchasing equipment that does not perform at the desired level is avoided since the same manufacturing infrastructure is utilized. To the extent that the reused design does not fall into the category of 'over-designed for the application', costs can be expected to diminish as discussed above. Thus, environmental risk is reduced through increased relatedness complexity. It should be noted that this conclusion is likely to be contingent on a variety of factors including scale economies, conformance quality levels, the cost of engineering hours, and total variable cost for the new verses the reused design. Hence TCE offers theoretical explanations for the impact of complexity on cost.

### 3.13 Summary

There are four principles emerging from TPF and TCE that influence cost / volume interactions; 1) diminishing returns; 2) utilization; 3) learning / experience; and 4) uncertainty. Diminishing returns results from the nonlinear relationships between improvement and cost as the gap between operating and asset frontiers is narrowed by changes in product complexity. Utilization is improved or diminished as the operating frontier is moved closer to or farther from the asset frontier. The change in utilization can be reflected in scope economies whereby a common infrastructure is shared by several products or scale economies whereby one product is produced in larger and larger quantities. Learning and experience accrue through increased design utilization. TCE raises the issue of uncertainty by suggesting that a lower level of risk is preferable. Uncertainty and its associated risks may be reduced through risk pooling.

In conclusion, both Theory of Performance Frontiers and Transaction Cost Economics suggest that product complexity impacts supply chain performance outcomes. TPF suggests nonlinear cost curves (diminishing benefits to increasing levels of utilization) whereas TCE implies linear relationships (incremental increases for additional transactions). Unresolved is which theory better explains the relationships between multiplicity and similarity and the supply chain performance outcomes of cost and sales volume. Identifying the functional form of the relationships between various complexity factors and cost will reveal which theory better explains the phenomenon.

## 3.2 Hypotheses

Four areas of supply chain performance outcomes are characterized in the literature (Hayes & Wheelwright, 1984; Skinner, 1974a): flexibility, delivery, quality, and cost. This research focuses on the facets of cost that are posited to be most sensitive to aspects of product complexity, and for which data can be obtained. Additionally, this research will investigate relationships between dimensions of product complexity and sales volume.

### 3.21 Effects of Multiplicity on Supply Chain Costs

Conformance quality is the degree to which production outputs conform to product design specifications (i.e., absence of defects). As multiplicity increases, the effort dedicated to maintaining consistent quality levels through inspection activities, certification, and the like must increase. For example, with increasing numbers of items to sample, the number of samples must increase if a constant detection rate is to be maintained (Grant & Leavenworth, 1980; Kapur & Lamberson, 1977). While the effort dedicated to ensuring conformance quality through inspection increases with increasing multiplicity, the level of conformance quality actually produced is expected to decrease. This relationship is an application of the learning curve effect. Production learning increases with experience (output) at a decreasing rate (Wright, 1936). As multiplicity increases, fewer numbers are produced of each separate product. Thus, there is less opportunity for learning and associated quality related process improvements; learning being one mechanism by which the operating frontier can be pushed toward the asset frontier. Thus when learning is diminished, the operating frontier recedes from the asset frontier resulting in a diminished average outgoing quality level.

Failure theory predicts that increasing the number of items contained in a system will reduce reliability because the probability of a failure within the system is a multiplicative function of the failure rates for all items in the system (Kapur, 1982). In the case of this research, the items represent products or product families and the system represents the portfolio of products. Thus as the number of products within the portfolio increases, the number of failures will increase at a decreasing rate since all rates are expressed on a zero to one scale. This indicates a non-linear relationship between failure and multiplicity; failures will increase at a decreasing rate in the presence of increasing multiplicity.

The number of products in the portfolio, or that may enter the portfolio, has an impact on the engineering resources that can be committed to any single product. Given a fixed level of available engineering resources, there will be reduced design and testing resources available for each product when the number of products in the portfolio increases. Alternatively, more intense design and testing activity is possible if the total number of products is reduced. The net effect is that any given product is likely to be less reliable given a larger more divergent portfolio of products.

Therefore the combined effects of increased failure modes and a lower level of reliability for any given product, brought about from increased multiplicity, will lead to more product failures in the field, and higher associated warranty costs. This logic leads to hypothesis one.

> $H_1$: As product multiplicity increases, product warranty costs increase at a decreasing rate.

As additional products are added to a portfolio, inventory is added and safety stock levels increased. Assuming a uniform service level, inventory on hand increases following a square root function (Hadley & Whitin, 1963). Given the scenario of a fixed level of demand being met with a greater number of separate products (increased multiplicity), there is reduced demand per product. As the scenario moves from a lower to a higher level of multiplicity, additional inventory is requied to support the new products. The inventory increases as a function of demand and deletions attributable to reduced volume for existing products. Thus total inventory required to support a given level of demand should increase since growth from new products overcomes the reductions from reduced demand for existing products. This effect arises because of the nonlinear nature of the inventory requirements curve. New products added to inventory are at the beginning of the curve, which has a steep slope, whereas reductions in levels required for existing inventory are based upon a section of the curve which is flatter. The implication of this is an increase in the holding and financing costs. These cost impacts are consistent with the predictions of both TCE and TPF; TCE indicating an increase in costs from additional transactions and TPF a decrease in return on investment. The decreased return on inventory investment results from the increase in inventory required to maintain the same sales level. Thus hypothesis two.

> $H_2$: As product multiplicity increases, inventory costs increase at an increasing rate.

Adding new products to the portfolio has several ramifications to manufacturing operations that can be translated into cost. Learning curve theory indicates that labor productivity is diminished since there is less experience manufacturing each separate product (Wright, 1936), hence direct labor increases. There is also an increase in scrap or rework since the worker is more likely to create defective products. The increased number of products may result in smaller purchase volumes with any given supplier and consequently may mean that pricing discounts are foregone. Direct manufacturing costs, e.g. materials required and the labor to transform and assemble, will increase with increasing levels of multiplicity in a nonlinear manner because of the inability to capture quantity discounts, increased assembly effort, and the productivity diminishing effects of the experience curve. Therefore hypothesis three is offered.

$H_3$: As product multiplicity increases, direct manufacturing costs increase at an increasing rate.

Overhead costs grow nonlinearly with multiplicity, due to scope economies and the addition of overhead resources in amounts larger than the immediate need. For example, when storage capacity must be added to accommodate an increase in units, it is added by bringing on additional storage facilities. Generally these facilities are secured with the ability to handle additional growth. Similarly, procurement organizations will add additional resources when the number of part numbers to manage exceeds its capacity. These resources generally add capacity beyond the immediate need. For example a buyer to process requisitions is added before there is a full forty hours of work and e-procurement systems are introduced that can process more transactions than required at the time of installation. Then as the workload increases, the utilization of the buyer or e-procurement system increases. These are concrete examples of changes to the asset base and the utilization improvements through scale economies. This is representative of the performance frontier moving toward the asset frontier via improved utilization for a given asset level. Beyond these costs are engineering, development, certification, and qualification costs which will increase from providing additional products to the market. Further into the organization, there will be inventory increases, additional production tooling secured, and a host of other costs such as those from the increase in requisitions that must be processed, reconciled, and paid. Therefore hypotheses four is offered.

$H_4$: As product multiplicity increases, indirect costs increase at a decreasing rate.

3.22 Effects of Similarity on Supply Chain Cost

Across the supply chain, costs increase when there is less experience with the items manufactured. Replacing a product with one that has minor differences partially mitigates the deleterious impacts of the experience curve since much of the old product is retained. This allows personnel to apply their knowledge from the old product more fully to the replacement product; the result being better productivity, quality, and delivery. Existing manufacturing processes may be kept largely intact, thereby minimizing the purchase of additional equipment and enabling amortization of capital expenditures over a larger unit base, when products reuse in substantial form the architectural elements of the prior product. Since there is already some related experience with the product, forecasting will be more accurate, although there will remain some demand variability from the uncertainty of the market's response to the replacement product. Implications of improved forecasting include better utilization of productive assets because labor and equipment are not idle due to stock outs or overcapacity. Within the product development organization, there will be fewer additional costs incurred from the added design, certification, qualification, and related efforts that arise from additional products. In essence, the existing infrastructure is better utilized. Thus TPF predicts diminishing costs down to the point where the operating and asset frontiers meet. This is represented in hypothesis five.

> $H_5$: As product similarity increases, direct manufacturing costs decrease at a decreasing rate.

3.23 Effects of Multiplicity on Sales Volume

The principles of economics provide insight to the impacts on sales volume by the addition of products to the portfolio (McConnell, 1981). The first principle is that the demand curve is not linear. For example, if percentage of market supplied is on the Y-axis and a measure such as price is on the X-axis, the demand curve will be concave beginning at 100% served when the price is zero and decaying to 0% at some price greater than zero (see Figure 4). A similar relationship will exist with number of products offered to the market. There is one product which can meet the largest segment of demand, but not 100%, and other products that continue to vie for an ever smaller share of the remaining market. This is illustrated in Figure 5. This logic assumes that firms rationally choose to release products to capture as large a share of the target market as possible, that there is no cannibalization of the products currently on the market, and that the market size is fixed. These assumptions are necessary since the relationships between current products and those entering the market are extremely difficult to describe with certainty (Cooper et al., 1997b) and some simplification is required to illustrate the point. An alternative to the single product scenario discussed above is that a firm releases a suite of products into the market in an attempt to gain greater total share. This occurs when it is strategically infeasible to compete with a single model. In either case, the result is that additional models result in additional sales (Kekre & Srinivasan, 1990; Lancaster, 1979; Quelch & Kenny, 1994). This principle is consistent with the utilization principle revealed by TPF, where the market size is analogous to capacity (asset frontier) and sales volume generated analogous to machine utilization (operating frontier). Therefore hypothesis six is offered.

$H_6$: As product multiplicity increases, sales volume increases at a decreasing rate.

**Figure 4**
**Relationship of Price to Market Share**

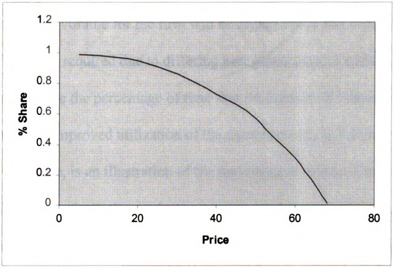
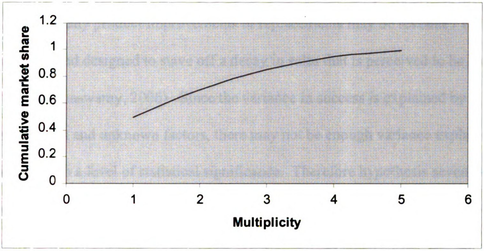


**Figure 5**
**Cumulative Market Share**




3.24 Effects of Similarity on Sales Volume

TPF implies better financial performance from improved asset utilization. This is seen in the example of the lathe presented in chapter 3. If the tool creates saleable parts 100% of the time, then the sales volume for the firm will be higher under full utilization than if the lathe is idled for setups required due to differing part geometries, materials, etc. Similarity acts to reduce the percentage of time that the lathe is idle through the reuse of product designs. The improved utilization of the manufacturing infrastructure, as represented by the lathe, is an illustration of the performance frontier moving closer to the asset frontier. Since similarity works to move the performance frontier toward the asset frontier, then all else being equal, similarity should have a positive impact on sales volume. However, other researchers have found that whether a product line replacement (similarity) will be successful depends on a large number of factors (Montoya-Weiss &

Calantone, 1994; Reddy, Holak, & Bhat, 1994). For example, some replacement products which are very similar to the predecessor are wildly successful, like Gillette's Mach 3 razor, while others such as 'new' Coke are detrimental (Smith, Ferrier, & Grimm, 2001). In fact, many product improvements or replacements may be revenue / sales volume neutral and designed to stave off a decay in sales that is perceived to be imminent (Mohan & Krishnaswamy, 2006). Since the variance in success is explained by a large number of known and unknown factors, there may not be enough variance explained by similarity to reach a level of statistical significance. Therefore hypothesis seven is presented as follows.

$H_7$: Changes in similarity will not be associated with sales volume.

## 4.0 Research Design and Methodology

### 4.1 Unit of Analysis

The unit of analysis for this research is the product portfolio. Specifically it is the portfolio of data processing devices offered to the market by a global designer and manufacturer of data processing equipment. Thus the conclusions about the impacts of complexity on supply chain costs and sales volume relate to the product portfolio.

### 4.2 Operationalizations of Variables

There are three categories of variables that are used in this research: independent variables (reflective of the two dimensions of complexity), control variables, and dependent variables. These variables can be found in Table 4 and rationales for their inclusion follow. Since the data set for this research comprises quarterly observations by brand, there are values for each of these variables across each brand and time period.

**Table 4**
**Variables**

| Variable Name | Description | Calculation | Category |
|---|---|---|---|
| # available | The number of products available in the portfolio | initial + added | Multiplicity / Static |
| % add | The percentage of the portfolio added in a period | added / initial | Multiplicity / Dynamic |
| % growth | The change in portfolio size | (added - terminations) / initial | Multiplicity / Dynamic |
| Percentage diversification | The relative degree of difference, based on age, in the portfolio | $(\Sigma_i\, p_i{*}\mathrm{Ln}\, 1/p_i)\ /\ (\mathrm{Ln}\, n)$ | Similarity / Static |
| % updated | The percentage of the products in the portfolio that are characterized as updates | updates in / total in | Similarity / Static |
| % updates entering | The percentage of products being added in a period that are updates | updates entering / total entering | Similarity / Dynamic |
| materials / unit | Total materials cost for the units sold in the period on a per unit basis | total materials cost / volume | Control |
| Delta materials / unit | The change in materials cost per unit | $(\mathrm{Material/unit})_t$ - $(\mathrm{Material/unit})_{t-1}$ | Control |
| volume | Number of units sold in the period | Given | Control / Dependent Variable |
| Delta Volume | The change in units sold | $\mathrm{Volume}_t$ - $\mathrm{Volume}_{t-1}$ | Control / Dependent Variable |
| Warranty | The total amount spent in the period on warranty | Given | Dependent Variable |
| Delta Warranty | The change in the warranty expenditure | $\mathrm{Warranty}_t$ - $\mathrm{Warranty}_{t-1}$ | Dependent Variable |
| Inventory | The dollar amount of inventory held (includes FGI, WIP, & Raw) | Given | Dependent Variable |
| Delta Inventory | The change in inventory investment | $\mathrm{Inventory}_t$ - $\mathrm{Inventory}_{t-1}$ | Dependent Variable |
| Indirect Cost | The total cost incurred in the period for indirect cost | Cost of Goods Sold - Direct Cost | Dependent Variable |
| Delta Indirect Cost | The change in indirect cost | $\mathrm{Indirect\ Cost}_t$ - $\mathrm{Indirect\ Cost}_{t-1}$ | Dependent Variable |
| Direct Cost | The total cost incurred in the period for direct cost | Given | Dependent Variable |
| Delta Direct Cost | The change in direct cost | $\mathrm{Direct\ Cost}_t$ - $\mathrm{Direct\ Cost}_{t-1}$ | Dependent Variable |

$p_i$ = product i's % of portfolio age
n = number of products in portfolio

### 4.21 Independent variables

*Multiplicity*

Measures that address multiplicity quantify the size of the portfolio by considering the portfolio in total and the additions to the portfolio. Larger values for these measures are consistent with an increase in portfolio complexity. Three separate measures of multiplicity are used. 'Number of products available' assesses issues pertaining to workload / resource requirement and scope / scale economies. 'Percent added' and 'percent growth' tap issues pertaining to learning and impacts that arise from changes to the portfolio size. 'Number of products available' is calculated by adding the number of products carried over from the prior period and those added to the portfolio during the period. It is the totality of products available to a customer in the period. 'Percent added' is the number of products entering the portfolio in the period divided by the number of products in the portfolio at the beginning of the period. 'Percent growth' is determined by subtracting the number of products withdrawn from the number of products added and dividing the result by the number of products in the portfolio at the beginning of the period.

*Similarity*

The three measures of similarity used in this research are presented in Table 4. They all measure the utilization of the existing infrastructure, but capture differing aspects. Two of the measures, 'percent updated' and 'percent updates entering' capture some variance pooling benefits. Both of these measures exploit the fact that entrances of products to the portfolio consist of products that are completely new and those that have little or no changes from a previous product. The study firm characterizes products as either new, refresh, or speed bump. New products are those that are brand new designs. Refreshes and speed bumps reuse existing design architecture. For example, speed bumps consist of an increase in the processor's clock speed; all else stays the same. Refreshed products could include nominal changes such as different warranty terms or the exchange of components possessing hazardous materials for those that are non-hazardous. This study aggregates speed bumps and refreshes and refers to them as 'updated' products. Thus greater levels of these 'updated' products within the portfolio correspond to greater levels of portfolio similarity. Thus the proportion of updated products is a measure of the similarity dimension of complexity.

Where measuring the percentage of updates will reveal more immediate impacts, a third measure of similarity, percentage diversification, captures differences between products that accumulate over time. The measure takes advantage of the fact that the data used in this research represent technologically dynamic products. Since the technology is changing rapidly, products released in year one may bear little resemblance to those introduced in year three. Later products may reflect advances in processing power, data storage technologies, communications technologies, or operating system software hard coded into the electronics. For example, processing technology has recently advanced from single core to multi-core architectures. Processors of a wholly different architecture were also introduced as technology from external sources became more advanced and widely accepted. Data storage has advanced from magnetic, to optical, and within optical the technology has advanced to allow greater storage density. Communications technologies have changed from electronic signals sent via copper wire to pulses of laser light sent across fiber optic cable. These technological differences drive physical and architectural differences at the product level. Therefore, greater differences in the age of products represented in the portfolio imply greater degrees of difference between products. Thus a higher level of age diversification implies a lower level of similarity. Age diversification is measured with an entropy calculation ($\Sigma_i\ p_i$*Ln $1/p_i$) where $p_i$ is the percentage of the total age represented within the portfolio by product i. This function has a maximum value of Ln n, n being the number of products summed. This property is used to make the measure comparable across brands by dividing the value of the entropy calculation by Ln n to arrive at the percentage of diversification. Thus lower percentages of age diversification imply greater levels of portfolio similarity.

4.22 Control variables

There are four explicit control variables used in this research: material cost per unit, sales volume, change in unit materials cost, and change in sales volume. Materials cost and change in materials cost are accounted for since they may influence several dependent variables of interest. A higher warranty cost could be associated with more expensive materials through the replacement of components under warranty. Inventory investment will increase with the cost of materials. Indirect cost may be influenced since the procurement organization may manage the supply chain more closely when unit cost of materials increases. Sales volume and the change in sales volume will impact all of the dependent variables. Volume increases may be associated with warranty cost increases since the absolute number of failures is likely to rise with volume. Volume increases will lead to increased inventory per the economic order quantity calculation. Direct and indirect costs may be impacted by learning curve effects and from an overall increase in workload.

4.23 Dependent Variables

*Warranty*

Warranty cost is a supply chain cost that is passed up the supply chain when problems arise with goods or services downstream. Warranty costs increase because customers return or request service for products that fail to function as expected. These failures may be from lack of conformance to manufacturing specification or from faulty materials that were not detected at the time of receipt. Customers will also initiate action when a product does not perform as expected. Thus the costs of warranty incorporate many types of quality issues. Warranty costs may occur from the time a product is delivered until the end of the warranty period. As such, time lags are incorporated in the analysis of warranty cost. The time lags are constrained to two periods in length due to the overall size of the data set. However, since electronic equipment often fails early in its life and since customers should be able to determine equipment functionality within this time window, the two period lag duration should be sufficient for detecting impacts of multiplicity and similarity on warranty cost. Since the cost of warranty relates to a direct linkage between customer and manufacturer, it is a supply chain cost and hence a variable of interest.

The warranty cost values in the data set used for this research include the total cost of materials for making repairs, the labor for completing the repair, and any shipping charges incurred in a given period. Additionally, the category captures any losses incurred due to customer returns of functional products e.g. the customer finds performance is too low and exchanges for a more powerful model.

*Inventory*

Inventory investment changes with changes in the number of unique stock keeping units required to assemble a product or a portfolio of products. Inventory investment is a supply chain outcome in that it represents the linkage between supplier and manufacturer. The investment will be directly related to the costs of inventory: holding, spoilage, stranding, and shrinkage. Hence insights gained measuring inventory investment will be directly transferable to inventory costs.

Effectively managing inventory has implications for improved financial performance at the manufacturer and influences supplier relationships. Inventory changes are likely to occur prior to products being released to market since raw materials inventory will grow in anticipation of demand and finished goods may be built ahead to ensure timely product delivery. Over time the inventory levels may be adjusted to account for better forecasting, different delivery lead times, or to better match demand. As such this study incorporates time lags of negative one, one, and two periods for the analysis the impacts of multiplicity and similarity on inventory.

The inventory values in the data set used for this research represent the aggregated dollar values of raw materials, work in process, and finished goods that are owned by the manufacturer.

*Cost of goods sold*

There are two categories of cost of goods sold used in this research; direct and indirect. Direct costs are those that are *directly* attributable to the product transformation process, for example assembling and mounting a power supply. The values for direct cost used in this data set include the cost of the materials required to build the product and the labor to assemble and transform them. The impact of multiplicity and similarity on direct cost should be seen in the initial period due to the immediacy of direct cost. It is incurred when the product is built. One and two period time lags are also investigated in addition to the initial period to determine the enduring effects of complexity changes.

Indirect costs are those that accrue from activities not related to the transformation process on a unit proportional basis, for example the cost of a commodity manager focusing on the supply of transformers. The values for indirect cost used in this data set are determined by subtracting the total direct cost from the total cost of goods sold. The residual, indirect cost, includes categories of costs such as the cost of procurement and engineering support. Where direct cost is incurred upon the assembly of a product, indirect cost is not constrained in this way. There could be long term effects found as employees adjust to different workloads or work that may have been postponed to accommodate the release of new products is performed in subsequent periods. Hence time lags of negative one, one, and two periods are employed in the analysis of the effects of multiplicity and similarity on indirect cost.

*Sales volume*

The number of units sold is an important outcome to measure because it represents the level of activity in the supply chain. Additionally, it is an indication of market success; products with higher sales volumes being more successful than those with lower sales volumes. In the data set used for this research, the sales volume represents the number of orders shipped. It is the shipping of a unit that invokes booking revenue and all costs associated with the production of the unit. The sales volume may not immediately change or respond fully to changes in the product portfolio. The market may take a while to embrace or become aware of products. As such, time lags of one and two periods are employed in the analysis of the effects of multiplicity and similarity on sales volume.

4.24 Models

The variables described above were combined to create 'static' and 'dynamic' models. The static models explain impacts of multiplicity and similarity on total costs whereas the dynamic models explain cost changes. These models are shown in Table 5.

**Table 5**
**Models**

## Static

| ID | Indepentent Variables | Dependent Variables |
|---|---|---|
| **Multiplicity** | | |
| Model 1a | # avail + # avail^2 + % divsfid + % updt + mtls + vol | Warranty, Inventory, Indirect Cost, Direct Cost |
| Model 1b | # avail + # avail^2 + % divsfid + % updt + mtls | Volume |
| **Similarity** | | |
| Model 2a | % updt + % updt^2 + # avail + mtls + vol | Warranty, Inventory, Indirect Cost, Direct Cost |
| Model 2b | % updt + % updt^2 + # avail + mtls | Volume |
| Model 3a | % divsfid + % divsfid^2 + # avail + mtls + vol | Direct Cost |
| Model 3b | % divsfid + % divsfid^2 + # avail + mtls | Volume |

## Dynamic

| ID | Indepentent Variables | Dependent Variables |
|---|---|---|
| **Multiplicity** | | |
| Model 4a | % add + % add^2 + % updt ent + dlta mtls + delta vol | Change in: Warranty, Inventory, Indirect Cost, Direct Cost |
| Model 4b | % add + % add^2 + % updt ent + delta mtls | Change in: Volume |
| Model 5a | % growth + % growth^2 + % updt ent + delta mtls + delta vol | Change in: Warranty, Inventory, Indirect Cost, Direct Cost |
| Model 5b | % growth + % growth^2 + % updt ent + delta mtls | Change in: Volume |
| **Similarity** | | |
| Model 6a | % updt ent + % prod add + delta mtls + delta vol | Change in: Direct Cost |
| Model 6b | % updt ent + % prod add + delta mtls | Change in: Volume |

## 4.3 Data

The data for this study comes from a designer and manufacturer of data processing equipment. Four product lines, referred to as brands, are represented and together represent a coherent segment of the business. These four brands represent 12% of the total revenue for the study company and 51% of revenue derived from manufactured goods. Each brand is targeted at a different market niche. The brand Brand 1 is targeted at the consumer market where volumes are high and average price is on the order of $4,000. These products tend to have shorter lives and as a consequence a greater amount of churn in the portfolio. Another brand, Brand 2, is focused on the high performance market and offers a scalable highly robust single package solution. A typical customer is an IT department and several of these units would be purchased in a single transaction. The average price for products within Brand 2 is on the order of $60,000. A third brand, Brand 3, uses proprietary architecture and open source software. The product is a multiprocessor architecture and offers energy economies over alternatives. The average price for Brand 3 products is on the order of $30,000. The final brand, referred to as Brand 4, comprises storage systems that can stand alone or be integrated with the other three brands. The primary customer is the corporate IT buyer who buys several units at a time. The average price for a Brand 4 product is $20,000. The four brands comprise the portfolio of products offered to several niches by a division of a larger organization.

The data come from a variety of sources which include financial statements for each brand, strategic planning documents, internal analyses of supply chain performance, and the like. For each brand, data are available for each of the twelve calendar quarters in the years 2004 through 2006. The data set is organized as products within models and models within brands. There are no missing data points. The data include not only brand level financial and sales information, but also similar information at the model level. The raw data collected that is pertinent to this research project includes the items listed in Table 6.

**Table 6**
**Data Categories**

| **Data Categories** |
|---|
| Number of products and models |
| Introduction dates for products and models |
| Termination dates for products and models |
| New vs. Replacement designation |
| Revenue for products and models |
| Sales volume for products and models |
| Gross profit by brand and model |
| Total cost by brand |
| Direct cost by brand |
| Indirect cost by brand |
| Materials cost by brand |
| Inventory cost by brand |
| Shipping cost by brand |
| Warranty cost by brand |

The data were transmitted as several dozen individual files. The files are primarily in spreadsheet form, but some are PowerPoint files. The PowerPoint files consist of presentations made to management as part of the company's regular planning process. The spreadsheets are those that are used in the process of managing the business and those supporting the PowerPoint presentations. These files are highly confidential as they provide information about release and withdrawal dates, sales volume, cost, and revenue data. The data were not disguised in any way by the company prior to its transmission for use in this research project.

The information within these files was combined, synthesized, and used in the creation of complexity measures. Since there were multiple data points from several different sources within the company, cross validation of the data was possible. There were very few data inconsistency problems. Most of the inconsistencies were related to misinterpretations and were resolved through discussions with personnel at the company. Any data that remained seemingly anomalous and unsubstantiated by the representatives of the company was not used. The result is a comprehensive and coherent data set for each of the four brands studied in which confidence can be placed relating to accuracy.

Confidence in the accuracy of the data set is possible for several reasons. First and foremost is the cross validation. Second is the discussion with multiple people from multiple functions within the company that were in positions to provide informed answers and opinions. Third is the understanding resulting from my personal experience working with similar data while employed by the company.

The data set includes quarterly observations of products, models, and brands; replications of the same units over time. For example direct manufacturing cost and sales volume are recorded at the end of each calendar quarter for each product and model. Therefore panel data regression is the method that is most appropriate for this research project.

### 4.4 Analytical Method

4.41 Overview of Panel Data Regression

Panel data regression is an econometric technique that offers several advantages over generic time series or cross sectional techniques. Panel data regression incorporates both of these techniques (Baltagi, 2001) thus enabling the detection and measurement of effects that are not discernable with time series or cross sectional analyses in isolation. Panel data regression also yields improved internal validity relative to the simultaneous evaluation of cross sections (Finkel, 2000; Keeves, 1988) through the use of effects that account for latent or omitted variables (Woolridge, 2002, 2003). This is important since omitted variables can lead to the biasing of parameter estimates. Panel data regression accounts for the omitted variables by partitioning the error into an unobserved effect plus idiosyncratic error which results in a more consistent parameter estimate (Woolridge, 2003).

Within panel data regression there are two options; fixed and random effects. An effect is fixed if it is time invariant and it is not the result of random variation, e.g. a brand retains its identity across time or seasons. A random effect is the result of random variation and must be uncorrelated with the regressor variables. The effects may be correlated across time or across groups. If there are correlations across either time or groups, then the analysis is considered to be a one way panel regression. If there are correlations with both time and groups, then the analysis is considered to be a two way panel regression.

4.42 Justification of Choice of Panel Data Regression

Panel data regression with fixed effects is the method employed for the analysis of the data collected for this study. The data for this study could be analyzed using time series methods, cross sectional methods, or panel data regression. Panel data regression is the preferred choice for four reasons (Baltagi, 2001). The first is that it controls for heterogeneity due to brands. Panel data regression has the ability to account for differences between these brands. Second, panel data regression is an effective technique to reveal changes over time attributable to a given driver. Hence it is used in this research to investigate changes to outcome variables attributable to changes in the level of product portfolio complexity. The third reason panel data regression is preferred is that it results in greater efficiency of estimators by accounting for omitted variables (Hsiao, 1986). Fourth, panel data regression offers the ability to detect and measure effects that cannot be found using time series or cross sectional techniques in isolation. An examples of such effects is measuring the effectiveness of fifth grade teachers within a school district. To do so fully requires the consideration of both time and classroom effects. Using time alone would not allow for comparisons between teachers, and using classroom alone would not capture changes in effectiveness (possibly measured by amount of knowledge mastered by a student) over time. Thus when there are changes over time and comparisons across groups or dissimilar groups are used, panel data regression is better suited than other techniques to explicate the relationships.

Since panel data regression was chosen as the analytical method, the determination of whether to use fixed or random effects was required. The choice depends on the interpretations that the researcher plans to make, the nature of the data collected, and assumptions made by the researcher about the data. One of the clearest distinctions about whether to use fixed or random effects entails the inference that will be drawn from the final results. If the intent is to infer population properties from the analysis of a sample of that population, then random effects are appropriate. However, if the intent is to make inference only about the population analyzed, then the use of fixed effects is recommended (Kennedy, 2003). The use of random effects requires the effects be attributable solely to random variation and be orthogonal to the independent variables. However, the fixed effects approach allows for endogeneity of regressors with the effect. Fixed effects are preferred when the number of time periods is large and the number of observations small. It is also preferred when the number of time periods is small and the number of observations large, given the condition of nonrandom cross sectional variation. In the event of uncertainty about the correlation between cross sectional variation and independent variables, using fixed effects is the more conservative approach since the estimates will remain unbiased.

There are three relevant assumptions pertinent to the use of fixed effects within panel data regression. The first is that the effect is not the result of random variation. Second is that the effect is time invariant. Last, the errors are assumed to be Gaussian and independently and identically distributed.

This study is not designed for the purpose of drawing inference to a larger population. As such inferences will be constrained to the data set. In the data set, the number of time periods is large relative to observations. The data manifest time invariant properties which are not random e.g. a product retains its identity across time and is rationally placed into a particular brand rather than whimsically assigned. Therefore, given the data for this study and the prudence of erring on the side of conservatism, the use of fixed effects in panel data regression was chosen for this study.

4.43 Analytical protocol

The data set was checked for outliers per the protocol recommended by Hair, Anderson, Tatham, and Black (1998). The data were standardized and checked to see if any data points exceeded 2.5 standard deviations from the mean. There were two periods within one brand where the number of products introduced exceeded this threshold and one point that came near it. As a result, related measures such as the percentage of new products in the portfolio and number of products available were also beyond the 2.5 sigma cutoff. Hair et al. indicate that the data points should be removed only if there is strong theoretical rationale for doing so. In this case there is justification for the removal of the data points. A conversation with the person who has tracked this data for the last six years at the study company revealed that the elevated levels are attributable the E.U.'s requirement that all products be free of hazardous substances. Additionally, the new product introductions were significantly elevated due to the introduction of several new models; each model having multiple products. The company was also slower than normal to remove products from the portfolio due to regional differences in the reduction of hazardous substances across marketing regions. Collectively these events are considered within the study company to be anomalous. They have not occurred in such magnitude prior or since. Thus there is sound reasoning to remove the three records associated with quarters two through four of 2006.

The data were then mean centered because nonlinear terms were going to be used. Mean centering is recommended with nonlinear terms because it eliminates extreme multicollinearity and renders all the regression coefficients meaningful (Cohen, Cohen, West, & Aiken, 2003).

Data analysis continued with the use of a Chow test (Chow, 1960) to ascertain the poolability of the data. Next, the appropriateness of a fixed effect for time and brand was established using an F test. In most cases both brand and time effects were indicated. The regression was then performed using either one or two way fixed effects as determined in the prior step. The overall model significance was determined with an F test and the significance of coefficients with T tests. Additionally, the covariance ratio was monitored to ensure no that no deleterious impacts to estimation efficiency were present.

Collinearity was checked by calculating variance inflation factors (VIF) for each model. The VIF's for models four through six were between one and two with one exception of a VIF of 2.3. However, the VIF's for models one through three, although generally less than 3.0, were slightly elevated but acceptable. Model 1A had two VIF's above 3.0; one at 3.2 and the other at 3.9. Model 2A also had two VIF's above 3.0; one at 5.2 and the other at 4.2. Model 3A had one VIF at 3.6.

Even though individually the VIF scores were acceptable, the impact of collinearity can be cumulative. To further, and more strenuously, test for collinearity partial and semi partial correlations were calculated and compared. Large differences between these two values indicate the presence of collinearity. There is only one instance where this comparison indicated the presence of collinearity; the prediction of a negative one period lag for indirect cost by model 1A. For this case, the use of weighted least squares was employed with direct cost per unit as the weight. This choice of weight was made because of its negative correlation with indirect cost and all of the independent variables except materials cost per unit. A reanalysis of the model using weighted least squares resulted in VIF's below 2.0 and no significant differences between the partial and semi partial correlations. Thus all results reported relating to model 1A's prediction of the negative one period lag of indirect cost are based on the application of weighted least squares.

## Table 7
## Correlation Matrixes

### Static Model Variables

| | Average | Standard deviation | Number of products available | Number of products available$^2$ | Percent diversified | Percent diversified$^2$ | Percentage of updated products | Percentage of updated products$^2$ | Materials cost per unit | Sales volume | Warranty | Inventory | Direct cost | Indirect cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of products available | 104.1 | 108 | 1 | | | | | | | | | | | |
| Number of products available$^2$ | 13959 | 18571 | 0.125 | 1 | | | | | | | | | | |
| Percent diversified | 0.937 | 0.032 | -0.397** | 0.171 | 1 | | | | | | | | | |
| Percent diversified$^2$ | 0.879 | 0.06 | -.486** | 0.163 | 0.177 | 1 | | | | | | | | |
| Percentage of updated products | 0.05 | 0.07 | 0.306* | 0.166 | -0.247 | -0.264 | 1 | | | | | | | |
| Percentage of updated products$^2$ | 0.004 | 0.007 | 0.243 | -0.005 | -0.123 | -0.191 | 0.778** | 1 | | | | | | |
| Materials cost per unit | 81088 | 108884 | -.594** | 0.112 | -0.076 | 0.231 | -0.080 | -0.081 | 1 | | | | | |
| Sales volume (# units) | 3998 | 3040 | 0.646** | 0.195 | -0.203 | -0.365* | 0.675** | 0.417** | -0.329* | 1 | | | | |
| Warranty ($ MM) | 38.8 | 21.5 | 0.860** | -0.167 | -0.530** | -0.425** | 0.049 | 0.075 | -0.406** | 0.381** | 1 | | | |
| Inventory ($ MM) | 185.9 | 101.4 | 0.008 | -0.183 | -0.512** | -0.024 | -0.366* | -0.229 | 0.410** | -0.318* | 0.367* | 1 | | |
| Direct cost ($ MM) | 236.4 | 224.1 | 0.479** | 0.224 | -0.283 | -0.320* | 0.667** | 0.405** | 0.013 | 0.929** | 0.302* | -0.106 | 1 | |
| Indirect cost ($ MM) | 76.1 | 31.9 | 0.776** | -0.194 | -0.591** | -0.387** | -0.047 | -0.007 | -0.285 | 0.273 | 0.974** | 0.534** | 0.246 | 1 |

* significant at 0.05
** significant at 0.01

**Table 7**
**Continued**

## Dynamic Model Variables

| | Average | Standard Deviation | Percentage added | (Percentage added)$^2$ | Portfolio growth | (Portfolio growth)$^2$ | Percentage entering as updates | Delta material cost per unit | Delta volume | Delta warranty | Delta inventory | Delta direct cost | Delta indirect cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage added | 0.146 | 0.148 | 1 | | | | | | | | | | |
| (Percentage added)$^2$ | 0.043 | 0.064 | 0.608** | 1 | | | | | | | | | |
| Percent portfolio growth | 0.05 | 0.181 | 0.670** | 0.405** | 1 | | | | | | | | |
| (Percent portfolio growth)$^2$ | 0.034 | 0.077 | 0.051 | 0.222 | -0.484** | 1 | | | | | | | |
| Percentage entering as updates | 0.238 | 0.344 | 0.546** | 0.257 | 0.281 | -0.056 | 1 | | | | | | |
| Delta material cost per unit | 11.5 | 72.9 | 0.030 | -0.033 | -0.106 | -0.016 | 0.287 | 1 | | | | | |
| Delta volume (# units) | 3137 | 20272 | 0.061 | -0.195 | -0.068 | -0.088 | 0.006 | 0.27 | 1 | | | | |
| Delta warranty ($ MM) | 1.41 | 6.64 | -0.139 | -0.456** | -0.22 | -0.058 | -0.034 | 0.355* | 0.442** | 1 | | | |
| Delta inventory ($ MM) | 1.42 | 34.8 | 0.127 | 0.828 | 0.182 | 0.042 | -0.079 | -0.354* | -0.074 | -0.531** | 1 | | |
| Delta direct cost ($ MM) | 11.7 | 73.1 | -0.091 | -0.207 | -0.264 | -0.074 | 0.087 | 0.642** | 0.650** | 0.564** | -0.446** | 1 | |
| Delta indirect cost ($ MM) | 1.86 | 8.5 | -0.133 | -0.490** | -0.201 | -0.038 | 0.027 | 0.291 | 0.426** | 0.839** | -0.385** | 0.507** | 1 |

* significant at 0.05
** significant at 0.01

## 5.0 Results

The panel data regression results reported below were created using the Proc Panel procedure in SAS 9.1. Other regressions and correlations were carried out using SPSS 16.0. The panel data regressions were carried out in a hierarchical manner with control variables and fixed effects entered first, followed by the linear complexity variable, and lastly the nonlinear complexity term entered. All of the p-values are based upon two tail tests.

Post hoc analyses were carried out to confirm that the relationship found when analyzing the four brands together was consistent with the relationship found within each brand. This was required since the fixed effects account for only intercept changes and not changes to the slope. Discrepancies between individual brands and the amalgam of the brands only appeared in testing hypotheses two and four.

The analyses incorporated significant efforts to detect and ameliorate the effects of collinearity. Collinearity was a concern since several correlations (see Table 7) were high. Specifically, within the static models, the correlation between the number of products available and warranty cost, number of products available and indirect cost, percentage of updated products and its squared term, sales volume and direct cost, and indirect cost and warranty cost. The high correlations within the data influenced which measures of complexity could be used within this research. Several were set aside due to elevated levels of collinearity.

## 5.1 Hypothesis 1

Hypothesis 1 states that warranty cost will increase at a decreasing rate with increasing levels of multiplicity. Three operationalizations of multiplicity were used to create models describing the impact of multiplicity on warranty cost: 1) the number of products in the portfolio, 2) the percentage of products added to the portfolio in a given period, and 3) percentage of portfolio growth. Warranty and the change in warranty costs were regressed on the independent and control variables with and without lagged effects. Tables 8 – 12 display the hierarchical regression results for the models with significant coefficients for the multiplicity variables.

# Table 8
# Model 1a – Warranty – no lag

| Hierarchical Regression: Model 1a<br>DV = Warranty   Time lag = 0 | | | |
|---|---|---|---|
| BE-1 | -18.0 | -7.01 | 7.67 |
| | 0.286 | 0.749 | 0.727 |
| BE-2 | **-46.6** | **-42.5** | -6.74 |
| | **<0.001** | **<0.001** | 0.720 |
| BE-3 | **-32.8** | **-27.6** | 8.17 |
| | **<0.001** | **<0.001** | 0.674 |
| TE-1 | **-18.1** | **-17.7** | **-16.2** |
| | **<0.001** | **<0.001** | **0.001** |
| TE-2 | **-17.1** | **-16.6** | **-15.5** |
| | **<0.001** | **<0.001** | **0.001** |
| TE-3 | **-20.8** | **-20.1** | **-19.8** |
| | **<0.001** | **<0.001** | **<0.001** |
| TE-4 | **-11.6** | **-10.2** | **-10.8** |
| | **0.013** | **0.039** | **0.024** |
| TE-5 | **-18.1** | **-18.2** | **-20.1** |
| | **<0.001** | **<0.001** | **<0.001** |
| TE-6 | **-13.3** | **-13.3** | **-16.2** |
| | **0.004** | **0.004** | **<0.001** |
| TE-7 | **-13.2** | **-13.3** | **-15.8** |
| | **0.004** | **0.004** | **<0.001** |
| TE-8 | -3.92 | -3.49 | -4.62 |
| | 0.367 | 0.428 | 0.273 |
| TE-9 | **-10.8** | **-11.8** | **-10.8** |
| | **0.025** | **0.020** | **0.024** |
| TE-10 | **-9.30** | **-9.46** | **10.3** |
| | **0.042** | **0.041** | **0.021** |
| TE-11 | **-10.4** | **-10.4** | **-10.1** |
| | **0.032** | **0.033** | **0.029** |
| Intercept | **76.0** | **71.1** | **61.5** |
| | **<0.001** | **<0.001** | **<0.001** |
| $mtrl/unit | -0.0005 | -0.0006 | -0.0004 |
| | 0.487 | 0.404 | 0.535 |
| sales vol | -0.0003 | -0.0002 | -0.0007 |
| | 0.771 | 0.808 | 0.472 |
| # prod avail | | 0.037 | **0.257** |
| | | 0.437 | **0.038** |
| # prod avail$^2$ | | | **-0.001** |
| | | | **0.054** |
| % update | -5.26 | -11.7 | -29.5 |
| | 0.81 | 0.620 | 0.223 |
| % diversified | **-93.5** | **-89.4** | -69.5 |
| | **0.040** | **0.053** | 0.116 |
| $R^2$ | 0.967 | 0.968 | 0.972 |

E = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

## Table 9
## Model 4a – Delta Warranty – no lag

| Hierarchical Regression: Model 4a DV = Delta Warranty Time lag = 0 | | | |
|---|---|---|---|
| BE-1 | -3.57 | -2.80 | 0.800 |
| | 0.283 | 0.403 | 0.818 |
| BE-2 | -1.85 | -3.54 | 0.394 |
| | 0.504 | 0.253 | 0.906 |
| BE-3 | -1.24 | -1.56 | 0.906 |
| | 0.632 | 0.547 | 0.732 |
| Intercept | 2.72 | 3.01 | **3.16** |
| | 0.176 | 0.135 | **0.097** |
| delta $mtrl/unit | **0.0004** | **0.0004** | **0.0005** |
| | **0.062** | **0.088** | **0.038** |
| delta sales vol | **0.0001** | **0.0001** | **0.0001** |
| | **0.006** | **0.005** | **0.054** |
| % prod add | | -11.5 | 6.55 |
| | | 0.227 | 0.574 |
| $(\% \text{ prod add})^2$ | | | **-116.2** |
| | | | **0.021** |
| % updates entering | 0.750 | 3.01 | -1.11 |
| | 0.832 | 0.450 | 0.787 |
| $R^2$ | 0.306 | 0.334 | 0.429 |

E = Fixed effect for brand
E = Fixed effect for time

| B term |
|---|
| p-value |

**Table 10**
**Model 4a – Delta Warranty – lag 1**

| **Hierarchical Regression: Model 4a DV = Delta Warranty Time lag = 1** | | | |
|---|---|---|---|
| BE-1 | -2.28 | -3.90 | -6.29 |
| | 0.550 | 0.324 | 0.121 |
| BE-2 | -1.57 | 0.584 | -2.69 |
| | 0.632 | 0.871 | 0.488 |
| BE-3 | -1.22 | -1.07 | -2.98 |
| | 0.688 | 0.720 | 0.332 |
| Intercept | 2.33 | 2.11 | 1.92 |
| | 0.317 | 0.358 | 0.386 |
| delta $mtrl/unit | -0.00007 | -0.00003 | -0.00005 |
| | 0.706 | 0.916 | 0.831 |
| delta sales vol | **0.0002** | **0.0001** | **0.0001** |
| | **0.006** | **0.007** | **0.021** |
| % prod add | | 15.8 | 0.190 |
| | | 0.168 | 0.989 |
| (% prod add)$^2$ | | | **99.6** |
| | | | **0.067** |
| % updates entering | -1.73 | -4.56 | -1.38 |
| | 0.668 | 0.310 | 0.765 |
| $R^2$ | 0.237 | 0.282 | 0.357 |

E = Fixed effect for brand
E = Fixed effect for time

| B term |
|---|
| p-value |

## Table 11
## Model 5a – Delta Warranty – no lag

| Hierarchical Regression: Model 5a DV = Delta Warranty Time lag = 0 | | | |
|---|---|---|---|
| TE-1 | **-7.43** | **-7.40** | **-7.14** |
| | **0.036** | **0.042** | **0.035** |
| TE-2 | **-8.55** | **-8.49** | **-6.83** |
| | **0.019** | **0.025** | **0.056** |
| TE-3 | 0.269 | 0.279 | 1.04 |
| | 0.938 | 0.936 | 0.749 |
| TE-4 | **-15.9** | **-15.8** | **-16.3** |
| | **0.003** | **0.004** | **0.002** |
| TE-5 | -5.28 | -5.26 | -5.00 |
| | 0.120 | 0.128 | 0.121 |
| TE-6 | **-8.47** | **-8.44** | **-8.43** |
| | **0.016** | **0.019** | **0.013** |
| TE-7 | 1.05 | 0.990 | 4.11 |
| | 0.756 | 0.779 | 0.252 |
| TE-8 | **-15.5** | **-15.4** | **-16.2** |
| | **0.001** | **0.002** | **<0.001** |
| TE-9 | **-11.7** | **-11.8** | **-10.9** |
| | **0.001** | **0.002** | **0.002** |
| TE-10 | **-7.24** | **-7.19** | **-7.04** |
| | **0.045** | **0.055** | **0.045** |
| TE-11 | **8.53** | **8.50** | **8.86** |
| | **0.002** | **0.003** | **<0.001** |
| Intercept | -0.0002 | -0.0002 | -0.0003 |
| | 0.522 | 0.538 | 0.314 |
| delta $mtrl/unit | 0.00008 | 0.000008 | -0.0002 |
| | 0.894 | 0.887 | 0.675 |
| Port Growth | | -0.351 | -4.95 |
| | | 0.943 | 0.327 |
| (Port Growth)$^2$ | | | **-25.1** |
| | | | **0.026** |
| % updates entering | -0.973 | -0.923 | -0.810 |
| | 0.662 | 0.697 | 0.714 |
| $R^2$ | 0.659 | 0.659 | 0.715 |

E = Fixed effect for brand
E = Fixed effect for time

| B term |
|---|
| p-value |

**Table 12**
**Model 5a – Delta Warranty – lag 2**

| **Hierarchical Regression: Model 5a DV = Delta Warranty Time lag = 2** | | | |
|---|---|---|---|
| TE-1 | -0.446 | 0.718 | 0.722 |
| | 0.901 | 0.834 | 0.837 |
| TE-2 | **-13.3** | **-11.5** | **-11.5** |
| | **0.003** | **0.007** | **0.009** |
| TE-3 | -5.30 | -4.31 | -4.31 |
| | 0.145 | 0.210 | 0.221 |
| TE-4 | **-8.17** | -6.20 | -6.21 |
| | **0.061** | 0.137 | 0.145 |
| TE-5 | 0.706 | 1.76 | 1.77 |
| | 0.842 | 0.603 | 0.610 |
| TE-6 | **-13.6** | **-12.5** | **-12.5** |
| | **0.002** | **0.002** | **0.003** |
| TE-7 | **-11.9** | **-13.0** | **-13.1** |
| | **0.002** | **<0.001** | **0.001** |
| TE-8 | -6.43 | -5.15 | -5.15 |
| | 0.116 | 0.184 | 0.195 |
| Intercept | **8.04** | **7.10** | **7.09** |
| | **0.004** | **0.008** | **0.010** |
| delta $mtrl/unit | 0.000004 | 0.00001 | 0.00001 |
| | 0.989 | 0.963 | 0.962 |
| delta sales vol | 0.00004 | 0.00004 | 0.00004 |
| | 0.456 | 0.469 | 0.478 |
| Port Growth | | **-10.00** | **-9.90** |
| | | **0.052** | **0.090** |
| $(\text{Port Growth})^2$ | | | 0.488 |
| | | | 0.966 |
| % updates entering | -0.459 | 1.14 | 1.14 |
| | 0.853 | 0.644 | 0.653 |
| $R^2$ | 0.679 | 0.728 | 0.729 |

E = Fixed effect for brand
E = Fixed effect for time

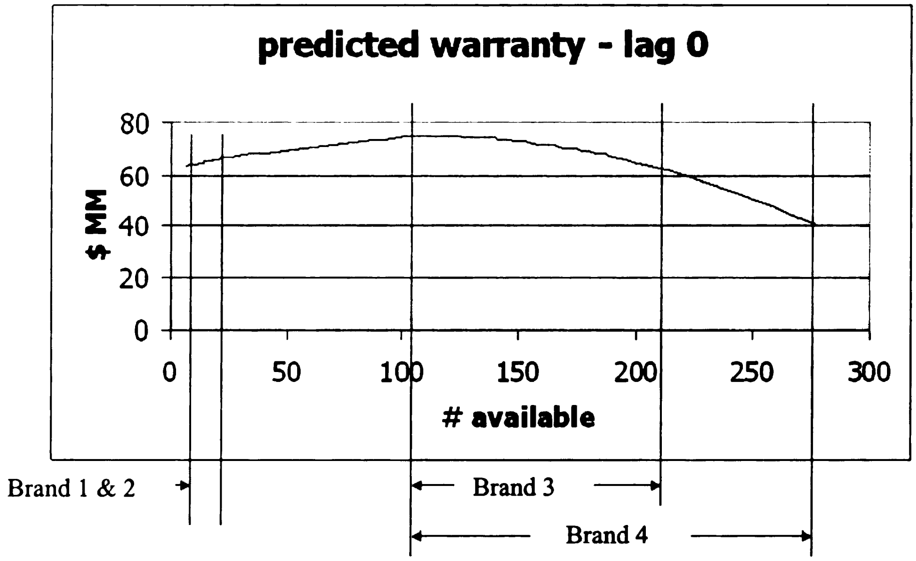
| B term |
|---|
| p-value |

Model 1a uses the number of products available as the operationalization of multiplicity whereas model 4a uses the percentage of products added to the portfolio and model 5a uses the percentage of portfolio growth. All three models use second order polynomials to test the relationship between multiplicity and warranty cost.

Model 1a

The hierarchical regressions for model 1a reveal the coefficients for the linear and non-linear multiplicity variables are significant at the 0.05 level for the no lag scenario, the linear being positive and the nonlinear negative. The result when plotted over the range of data is an inverted U shaped curve (see Figure 6). While the overall model explains 97.2% of the variance in warranty cost the fixed effects and controls account for 96.7%.

**Figure 6**
**Hypothesis 1 Model 1a**




To confirm the validity of the shape of the curve each brand was plotted. If each brand manifests the same general pattern, then the confidence can be placed in the curve. However, if plots of the individual brands manifest different patterns, then the result is an interaction of brand effects. In this case, the brand level plots reveal two distinct populations; two that increase linearly and thus provide partial support for the hypothesis, and two that decline exponentially.

Because the individual plots discussed above are likely errant due to their creation using the coefficient from the regression equation that had interacting brand effects adversely impacting it, separate regressions were performed on each brand using just the complexity variables. The reduced number of variables was required due to the small number of data points for each brand. The result is that brands x and p do not have any statistically significant relationships with warranty cost. However, Brand 4 shows a linear increase ($B = 0.571$, $p=0.095$) in warranty cost with an increase in complexity and Brand 2 manifests a nonlinear increase ($B_{lin} = 18.4$, $p=0.036$ and $B_{nl} = 0.99$,$p=0.037$). Thus the partial support of the hypothesis is confirmed.

In the process of addressing the counter intuitive finding shown in Figure 6 a logarithmic function form was investigated. The outcome is that the logarithmic form of the complexity variables explain a greater amount of variance than the polynomial form (18.7% vs. 15.5%). Furthermore, the logarithmic form does not suffer from the interaction of fixed effects as evidence by each plot manifesting the same general shape. The significance of the logarithmic relationship fully supports the hypothesis.

<u>Model 4a</u>

The hierarchical regressions for model 4a reveal the coefficients for the non-linear multiplicity variables are significant at the 0.05 level for the no lag and one period lag scenarios. The coefficient is negative in the no lag scenario and positive for one period lag. The result of plotting the no lag scenario over the range of data is a curve which decreases at an increasing rate (see Figure 7) and the result of plotting the one period lag scenario is a curve which increases at an increasing rate (see Figure 8). The multiplicity variables in Model 4a explain an additional approximately 12% of the variance in the change in warranty cost beyond the fixed effects and controls; the no lag scenario increasing from 30.6% to 42.9% and the one period lag scenario from 23.7% to 35.7%.

**Figure 7**
**Hypothesis 1 Model 4a – no lag**

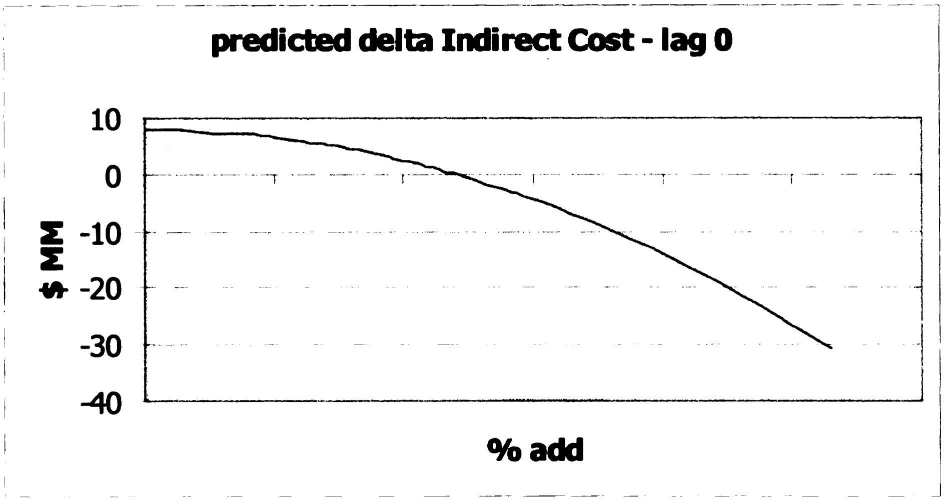
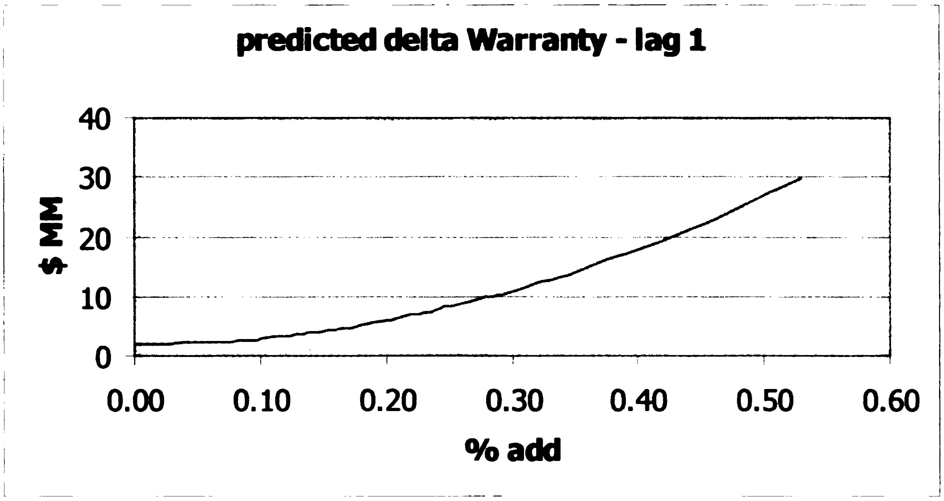


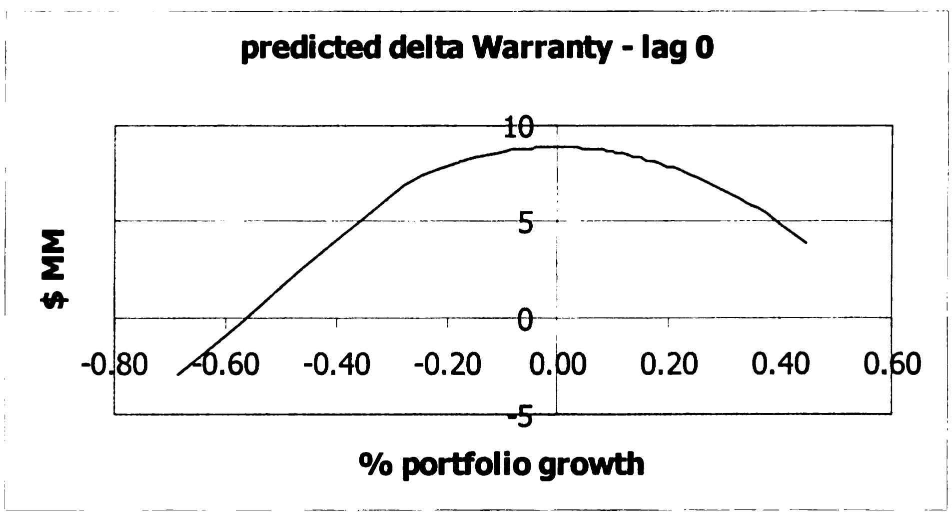

**Figure 8**
**Hypothesis 1 Model 4a – lag 1**



Model 5a

The hierarchical regressions for model 5a reveal the coefficient for the non-linear multiplicity variable is negative and significant at the 0.05 level for the no lag scenario. and the coefficient for the linear multiplicity term is negative and significant at the 0.05 level in the two period lag scenario. The result of plotting the significant multiplicity variables over the range of data in the no lag scenario is an inverted U shaped curve (see Figure 9). The total variance in change in warranty cost explained by the model for the no lag scenario is 71.5% with the controls and fixed effects explaining 65.9% and two period lag scenario shows 72.9% of variance explained with 67.9% coming from controls and fixed effects.

**Figure 9**
**Hypothesis 1 Model 5a**



Summary

Support for the hypothesis is found with the static model in the no lag scenario. Partial support is found with model 4a with one period lag and model 5a in the no lag scenario. Model 4a in the no lag scenario and model 5a in the two period lag scenario present relationships opposite to that hypothesized.

### 5.2 Hypothesis 2

Hypothesis 2 states that inventory investment will increase at an increasing rate with increasing levels of multiplicity. Three operationalizations of multiplicity were used to create models describing the impact of multiplicity on warranty cost: 1) the number of products in the portfolio, 2) the percentage of products added to the portfolio in a given period, and 3) percentage of portfolio growth. Inventory and change in inventory investment wer regressed upon the independent and control variables with and without lagged effects. Tables 13 – 15 display the hierarchical regression results for the models with significant coefficients for the multiplicity variables.

**Table 13**
**Model 4a – Delta Inventory – lag 2**

| **Hierarchical Regression: Model 4a DV = Delta Inventory Time lag = 2** | | | |
|---|---|---|---|
| BE-1 | -10.1 | -17.7 | -7.99 |
| | 0.663 | 0.471 | 0.747 |
| BE-2 | -16.7 | -7.29 | 7.32 |
| | 0.411 | 0.744 | 0.760 |
| BE-3 | -12.1 | -13.0 | -6.12 |
| | 0.515 | 0.488 | 0.745 |
| Intercept | 6.23 | 5.69 | 7.88 |
| | 0.659 | 0.687 | 0.571 |
| delta $mtrl/unit | -0.002 | -0.002 | -0.002 |
| | 0.117 | 0.150 | 0.157 |
| delta sales vol | -0.0002 | -0.0001 | -0.0001 |
| | 0.564 | 0.749 | 0.739 |
| % prod add | | 71.0 | **151.5** |
| | | 0.325 | **0.096** |
| (% prod add)$^2$ | | | -462.6 |
| | | | 0.148 |
| % updates entering | 23.0 | 9.54 | -5.83 |
| | 0.342 | 0.730 | 0.841 |
| $R^2$ | | 0.143 | 0.208 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 14**
**Model 5a – Delta Inventory – no lag**

| Hierarchical Regression: Model 5a DV = Delta Inventory Time lag = 0 | | | |
|---|---|---|---|
| TE-1 | **62.3** | **63.0** | **61.6** |
| | **0.005** | **0.005** | **0.004** |
| TE-2 | **63.2** | **64.6** | **55.8** |
| | **0.005** | **0.006** | **0.013** |
| TE-3 | **36.9** | **37.2** | 33.1 |
| | **0.082** | **0.086** | 0.108 |
| TE-4 | **56.4** | **58.8** | **61.7** |
| | **0.062** | **0.065** | **0.044** |
| TE-5 | **34.4** | **34.8** | **33.4** |
| | **0.095** | **0.097** | **0.094** |
| TE-6 | **55.4** | **56.1** | **56.1** |
| | **0.010** | **0.011** | **0.008** |
| TE-7 | 0.615 | -0.871 | -17.4 |
| | 0.976 | 0.967 | 0.429 |
| TE-8 | **61.5** | **63.2** | **67.7** |
| | **0.027** | **0.028** | **0.015** |
| TE-9 | **66.8** | **66.4** | **61.8** |
| | **0.002** | **0.003** | **0.004** |
| TE-10 | **66.8** | **70.2** | **69.4** |
| | **0.003** | **0.003** | **0.002** |
| Intercept | **-45.5** | **-46.2** | **-48.1** |
| | **0.005** | **0.006** | **0.003** |
| delta $mtrl/unit | -0.001 | -0.001 | -0.0007 |
| | 0.442 | 0.475 | 0.664 |
| delta sales vol | 0.0002 | 0.0002 | 0.0004 |
| | 0.489 | 0.470 | 0.225 |
| Port Growth | | -8.70 | 15.60 |
| | | 0.770 | 0.613 |
| $(\text{Port Growth})^2$ | | | **132.7** |
| | | | **0.052** |
| % updates entering | -7.39 | -6.15 | -6.75 |
| | 0.583 | 0.667 | 0.620 |
| $R^2$ | 0.546 | 0.548 | 0.606 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 15**
**Model 5a – Delta Inventory – lag 2**

| **Hierarchical Regression: Model 5A DV = Delta Inventory Time lag = 2** | | | |
|---|---|---|---|
| TE-1 | 31.3 | 24.8 | 24.9 |
| | 0.167 | 0.256 | 0.265 |
| TE-2 | **74.3** | **64.2** | **63.9** |
| | **0.006** | **0.015** | **0.018** |
| TE-3 | 32.6 | 27.1 | 27.1 |
| | 0.146 | 0.209 | 0.219 |
| TE-4 | **60.4** | **49.4** | **49.3** |
| | **0.027** | **0.062** | **0.069** |
| TE-5 | -1.55 | -7.39 | -7.29 |
| | 0.943 | -727 | 0.737 |
| TE-6 | **75.9** | **69.9** | **70.1** |
| | **0.004** | **0.005** | **0.007** |
| TE-7 | **65.3** | **71.6** | **71.1** |
| | **0.006** | **0.002** | **0.004** |
| TE-8 | **76.3** | **69.2** | **69.3** |
| | **0.005** | **0.008** | **0.009** |
| Intercept | **-49.3** | **-44.1** | **-44.3** |
| | **0.005** | **0.009** | **0.011** |
| delta $mtrl/unit | 0.0003 | 0.0003 | 0.0003 |
| | 0.833 | 0.847 | 0.847 |
| delta sales vol | 0.0004 | 0.0005 | 0.0005 |
| | 0.177 | 0.143 | 0.151 |
| Port Growth | | **55.6** | 56.9 |
| | | **0.082** | 0.118 |
| (Port Growth)$^2$ | | | 6.02 |
| | | | 0.993 |
| % updates entering | 2.94 | -5.96 | -6.02 |
| | 0.848 | 0.700 | 0.704 |
| $R^2$ | 0.537 | 0.595 | 0.595 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

Model 1a uses the number of products available as the operationalization of multiplicity whereas model 4a uses the percentage of products added to the portfolio and model 5a uses the percentage of portfolio growth. All three models use second order polynomials to test the relationship between multiplicity and inventory investment.

Model 1a

The hierarchical regressions using model 1a failed to detect a significant (<0.10) relationship between multiplicity and inventory investment. Low power is the likely source of the null result since it is only approximately 0.55 for the nonlinear term and nearly zero for the linear term.

Model 4a

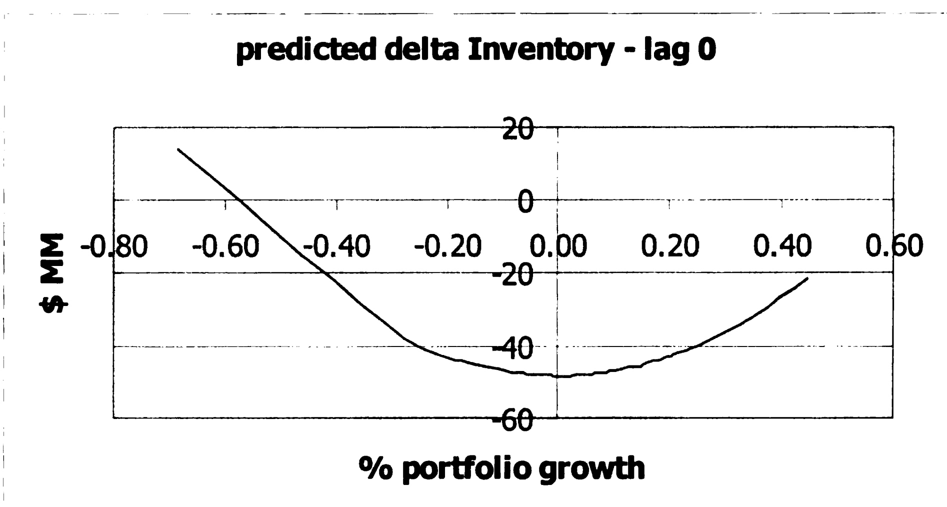
The hierarchical regressions for model 4a reveal the coefficient for the linear multiplicity variable is positive and significant at the 0.10 level for the no lag scenario. Thus the indication is an increase in inventory investment with increasing levels of multiplicity. The fixed effects and controls explain 11.2% of the variance in the change in inventory investment and the multiplicity variable adds another 9.6% to bring the total variance explained by the model to 20.8%.

Model 5a

The hierarchical regressions for model 5a reveal the coefficient for the non-linear multiplicity variable is significant and positive at the 0.05 level for the no lag scenario and the coefficient for the linear multiplicity term is positive and significant at the 0.10 level in the two period lag scenario. The result of plotting the significant multiplicity variable over the range of data for the no lag scenario is a U shaped curve (see Figure 10). The total variance in the change in inventory investment explained by the model for the no lag scenario is 60.6% with the controls and fixed effects explaining 54.6% and the two period lag scenario shows 59.5% of variance explained with 53.7% coming from controls and fixed effects.

To confirm the validity of the shape of the curve each brand was checked. If each brand manifests the same general pattern, then the confidence can be placed in the curve. However, if plots of the individual brands manifest different patterns, then the result is an interaction of brand effects. In this case, the shape of the curves for each brand are consistent with the curve shown in Figure 10.

**Figure 10**
**Hypothesis 2 Model 5a**



Summary

There is no support for the hypothesis from the static models. Partial support for the hypothesis is found with model 4a in the two period lag scenario and model 5a in the no lag and two period lag scenarios.

### 5.3 Hypothesis 3

Hypothesis 3 states that direct cost will increase at an increasing rate with increasing levels of multiplicity. Three operationalizations of multiplicity were used to create models describing the impact of multiplicity on warranty cost: 1) the number of products in the portfolio, 2) the percentage of products added to the portfolio in a given period, and 3) percentage of portfolio growth. Direct cost and change in direct cost were regressed on the independent and control variables with and without lagged effects. Tables 16 – 18 display the hierarchical regression results for the models with significant coefficients for the multiplicity variables.

**Table 16**
**Model 4a – Delta Direct Cost – no lag**

| Hierarchical Regression: Model 4a DV = Delta Direct Cost Time lag = 0 | | | |
|---|---|---|---|
| BE-1 | 24.1 | 34.4 | 35.2 |
| | 0.294 | 0.120 | 0.156 |
| BE-2 | 17.6 | -5.01 | -4.12 |
| | 0.360 | 0.803 | 0.860 |
| BE-3 | 16.0 | 11.7 | 12.3 |
| | 0.377 | 0.489 | 0.511 |
| Intercept | -6.95 | -2.99 | -2.96 |
| | 0.614 | 0.818 | 0.822 |
| delta $mtrl/unit | **0.010** | **0.009** | **0.009** |
| | **<0.001** | **<0.001** | **<0.001** |
| delta sales vol | **0.002** | **0.002** | **0.002** |
| | **<0.001** | **<0.001** | **<0.001** |
| % prod add | | **-153.7** | **-149.7** |
| | | **0.016** | **0.074** |
| (% prod add)$^2$ | | | -26.2 |
| | | | 0.939 |
| % updates entering | -16.0 | 14.3 | 13.3 |
| | 0.515 | 0.582 | 0.645 |
| $R^2$ | 0.724 | 0.766 | 0.766 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 17**
**Model 5a – Delta Direct Cost – no lag**

| Hierarchical Regression: Model 5a DV = Delta Direct Cost Time lag = 0 | | | |
|---|---|---|---|
| TE-1 | -42.2 | -34.2 | -32.7 |
| | 0.188 | 0.252 | 0.263 |
| TE-2 | -32.5 | -15.6 | -6.4 |
| | 0.315 | 0.611 | 0.835 |
| TE-3 | -14.3 | -11.5 | -7.3 |
| | 0.652 | 0.696 | 0.802 |
| TE-4 | -17.9 | 9.45 | 6.39 |
| | 0.690 | 0.827 | 0.880 |
| TE-5 | -30.6 | -25.4 | -24.0 |
| | 0.324 | 0.377 | 0.696 |
| TE-6 | -49.4 | -41.5 | -41.4 |
| | 0.119 | 0.159 | 0.152 |
| TE-7 | -20.6 | -37.6 | -20.3 |
| | 0.510 | 0.212 | 0.520 |
| TE-8 | -44.2 | -25.5 | -30.2 |
| | 0.283 | 0.570 | 0.429 |
| TE-9 | **-51.5** | **-56.8** | **-52.0** |
| | **0.101** | **0.055** | **0.074** |
| TE-10 | -21.7 | -6.07 | -5.25 |
| | 0.502 | 0.843 | 0.861 |
| Intercept | 36.7 | 28.8 | 30.8 |
| | 0.122 | 0.193 | 0.158 |
| delta $mtrl/unit | **0.009** | **0.010** | **0.009** |
| | **<0.001** | **<0.001** | **0.004** |
| delta sales vol | **0.002** | **0.002** | **0.002** |
| | **<0.001** | **<0.001** | **<0.001** |
| Port Growth | | **-99.9** | **-125.4** |
| | | **0.022** | **<0.001** |
| (Port Growth)$^2$ | | | -139.3 |
| | | | 0.151 |
| % updates entering | 1.20 | 15.4 | 16.0 |
| | 0.953 | 0.442 | 0.415 |
| $R^2$ | 0.759 | 0.800 | 0.814 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 18**
**Model 5a – Delta Direct Cost – lag 1**

| Hierarchical Regression: Model 5a DV = Delta Direct Cost Time lag = 1 | | | |
|---|---|---|---|
| TE-1 | -50.1 | -45.5 | -45.5 |
| | 0.183 | 0.217 | 0.199 |
| TE-2 | 5.21 | 3.19 | -6.27 |
| | 0.888 | 0.930 | 0.838 |
| TE-3 | -92.7 | **-85.5** | **-96.9** |
| | 0.450 | **0.060** | **0.030** |
| TE-4 | -65.5 | **-68.5** | **-69.1** |
| | 0.109 | **0.089** | **0.074** |
| TE-5 | -52.1 | -46.7 | -44.2 |
| | 0.166 | 0.207 | 0.213 |
| TE-6 | -15.5 | -11.5 | -5.70 |
| | 0.671 | 0.748 | 0.869 |
| TE-7 | **-108.5** | **-85.5** | **-115.3** |
| | **0.013** | **0.051** | **0.015** |
| TE-8 | **-71.3** | **-68.9** | **-65.6** |
| | **0.070** | **0.074** | **0.076** |
| TE-9 | -37.3 | -23.6 | -28.4 |
| | 0.329 | 0.538 | 0.440 |
| Intercept | **54.2** | **48.2** | **46.0** |
| | **0.049** | **0.075** | **0.077** |
| delta $mtrl/unit | **-0.006** | **-0.006** | **-0.005** |
| | **0.047** | **0.037** | **0.053** |
| delta sales vol | **0.001** | **0.001** | **0.001** |
| | **0.016** | **0.012** | **0.049** |
| Port Growth | | 76.6 | **119.7** |
| | | 0.149 | **0.038** |
| (Port Growth)$^2$ | | | **215.0** |
| | | | **0.081** |
| % updates entering | 6.05 | -6.21 | -4.98 |
| | 0.809 | 0.81 | 0.841 |
| $R^2$ | 0.693 | 0.717 | 0.750 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

Model 1a uses the number of products available as the operationalization of multiplicity whereas model 4a uses the percentage of products added to the portfolio and model 5a uses the percentage of portfolio growth. All three models use second order polynomials to test the relationship between multiplicity and direct cost.

Model 1a

The hierarchical regressions using model 1a failed to detect a significant (<0.10) relationship between multiplicity and direct cost; power is greater than 0.90.

Model 4a

The hierarchical regressions for model 4a reveal the coefficient for the linear multiplicity variable is negative and significant at the 0.05 level for the no lag scenario. Thus the indication is a decrease in direct cost with increasing levels of multiplicity. The fixed effects and controls explain 72.4% of the variance in the change in direct cost and adding the multiplicity variable brings the total variance explained by the model to 76.6%.

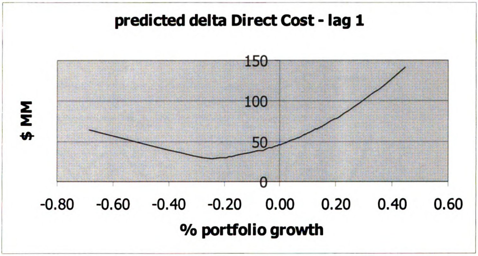
Model 5a

The hierarchical regressions for model 5a reveal the coefficient for the linear multiplicity variable is negative and significant at the 0.05 level for the no lag scenario. The total variance in the change in direct cost explained by the model is 81.4% with the controls and fixed effects explaining 75.9%. For the one period lag scenario the linear term is positive and significant at 0.05 and the non-linear is positive and significant at 0.10.

Graphing this function over the range of the data reveals a U shaped curve (see Figure 11). The variance explained by the controls and fixed effects is 69.3%. The multiplicity variables explain an additional 5.7% bringing the total variance explained by the model to 75.0%.

To confirm the validity of the shape of the curve each brand was checked. In this case, the shape of the curves for each brand are consistent with the curve shown in Figure 11.

**Figure 11**
**Hypothesis 3 Model 5a**




Summary

No support for the hypothesis is found using the static model. The dynamic models, 4a and 5a, provide mixed results. Models 4a and 5a find, contrary to that hypothesized, that direct cost decreases in the no lag scenario. However, model 5a finds complete support for the hypothesis in the one period lag scenario.

### 5.4 Hypothesis 4

Hypothesis 4 states that indirect cost will increase at a decreasing rate with increasing levels of multiplicity. Three operationalizations of multiplicity were used to create models describing the impact of multiplicity on warranty cost: 1) the number of products in the portfolio, 2) the percentage of products added to the portfolio in a given period, and 3) percentage of portfolio growth. Indirect cost and change in indirect cost were regressed on the independent and control variables with and without lagged effects. Tables 19 – 24 display the hierarchical regression results for the models with significant coefficients for the multiplicity variables.

**Table 19**
**Model 1a – Indirect cost – prior 1**

| Hierarchical Regression: Model 1a DV = Indirect Cost Time lag = -1 | | | |
|---|---|---|---|
| BE-1 | -16.8 | -24.9 | -15.7 |
| | 0.505 | 0.351 | 0.549 |
| BE-2 | 14.2 | 8.46 | 20.1 |
| | 0.536 | 0.720 | 0.402 |
| BE-3 | **56.0** | 41.9 | 19.2 |
| | **0.020** | 0.129 | 0.514 |
| TE-1 | 4.45 | 4.55 | 3.64 |
| | 0.283 | 0.273 | 0.366 |
| TE-2 | -0.979 | -0.655 | -0.275 |
| | 0.844 | 0.894 | 0.955 |
| TE-3 | **4.95** | **11.3** | **11.5** |
| | **0.082** | **0.057** | **0.046** |
| TE-4 | 1.30 | 0.773 | -1.02 |
| | 0.775 | 0.866 | 0.822 |
| TE-5 | 0.008 | -0.081 | -2.38 |
| | 0.999 | 0.986 | 0.601 |
| TE-6 | 3.93 | 4.05 | 1.4 |
| | 0.377 | 0.364 | 0.751 |
| TE-7 | **12.2** | **13.1** | **13.2** |
| | **0.023** | **0.018** | **0.014** |
| TE-8 | 8.84 | 7.11 | 6.97 |
| | 0.368 | 0.166 | 0.160 |
| TE-9 | **7.58** | **7.59** | **7.5** |
| | **0.097** | **0.097** | **0.088** |
| TE-10 | **12.63** | **11.93** | **10.9** |
| | **0.010** | **0.015** | **0.022** |
| Intercept | **56.9** | **64.0** | **73.2** |
| | **0.002** | **0.002** | **0.001** |
| $mtrl/unit | 0.0001 | 0.0002 | 0.0002 |
| | 0.488 | 0.346 | 0.329 |
| sales vol | 0.0003 | 0.00006 | 0.00003 |
| | 0.222 | 0.635 | 0.801 |
| # prod avail | | 0.052 | **0.268** |
| | | 0.332 | **0.067** |
| # prod avail$^2$ | | | 0.0004 |
| | | | 0.110 |
| % update | -1.80 | -10.5 | -21.4 |
| | 0.933 | 0.651 | 0.363 |
| % diversified | **-104.0** | **-96.0** | -57.2 |
| | **0.041** | **0.061** | 0.287 |
| $R^2$ | 0.977 | 0.978 | 0.980 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

## Table 20
## Model 1a – Indirect cost – no lag

| Hierarchical Regression: Model 1a DV = Indirect Cost Time lag = 0 | | | |
|---|---|---|---|
| BE-1 | **-42.2** | -25.8 | -1.96 |
| | **0.061** | 0.367 | 0.942 |
| BE-2 | -73.3 | **-67.2** | -4.02 |
| | **<0.001** | **<0.001** | 0.693 |
| BE-3 | **-44.5** | **-36.7** | 21.5 |
| | **<0.001** | **0.002** | 0.374 |
| TE-1 | **-18.0** | **-17.5** | **-14.9** |
| | **0.006** | **0.008** | **0.012** |
| TE-2 | **-13.5** | **-12.7** | **-11.0** |
| | **0.025** | **0.037** | **0.045** |
| TE-3 | **-18.8** | **-17.8** | **-17.3** |
| | **0.005** | **0.008** | **0.005** |
| TE-4 | **-10.8** | **-8.73** | **-9.57** |
| | **0.067** | **0.166** | **0.094** |
| TE-5 | **-19.0** | **-19.2** | **-22.3** |
| | **0.005** | **0.005** | **<0.001** |
| TE-6 | **-17.2** | **-17.3** | **-22.0** |
| | **0.004** | **0.004** | **<0.001** |
| TE-7 | **-13.3** | **-13.4** | **-17.6** |
| | **0.020** | **0.020** | **<0.001** |
| TE-8 | -3.58 | -2.94 | -4.78 |
| | 0.525 | 0.606 | 0.356 |
| TE-9 | -6.04 | -7.44 | -5.87 |
| | 0.317 | 0.236 | 0.248 |
| TE-10 | -7.04 | -7.28 | -8.60 |
| | 0.225 | 0.212 | 0.105 |
| TE-11 | -3.74 | -3.77 | -3.27 |
| | 0.535 | 0.534 | 0.547 |
| Intercept | **127.5** | **120.2** | **104.7** |
| | **<0.001** | **<0.001** | **<0.001** |
| $mtrl/unit | -0.00001 | -0.0001 | 0.0002 |
| | 0.990 | 0.912 | 0.825 |
| sales vol | 0.00008 | 0.000008 | -0.0006 |
| | 0.379 | 0.950 | 0.580 |
| # prod avail | | 0.055 | **0.414** |
| | | 0.372 | **0.009** |
| # prod avail$^2$ | | | **-0.002** |
| | | | **0.013** |
| % update | -26.7 | -36.2 | **-65.3** |
| | 0.352 | 0.241 | **0.034** |
| % diversified | **-153.3** | **-147.1** | **-114.8** |
| | **0.012** | **0.016** | **0.039** |
| $R^2$ | 0.974 | 0.975 | 0.981 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 21**
**Model 4a – Delta Indirect Cost – no lag**

| Hierarchical Regression: Model 4a DV = Delta Indirect Cost Time lag = 0 | | | |
|---|---|---|---|
| TE-1 | -0.601 | -0.578 | -2.34 |
| | 0.906 | 0.910 | 0.620 |
| TE-2 | -5.06 | -4.01 | -2.51 |
| | 0.331 | 0.450 | 0.607 |
| TE-3 | 3.36 | 3.76 | 0.912 |
| | 0.511 | 0.465 | 0.850 |
| TE-4 | **-15.5** | **-13.7** | **-13.8** |
| | **0.038** | **0.075** | **0.052** |
| TE-5 | -4.50 | -4.34 | -4.48 |
| | 0.366 | 0.384 | 0.327 |
| TE-6 | -1.14 | -0.809 | -0.635 |
| | 0.819 | 0.872 | 0.890 |
| TE-7 | 4.74 | 5.12 | 4.42 |
| | 0.347 | 0.313 | 0.342 |
| TE-8 | -9.26 | -8.28 | **-10.4** |
| | 0.165 | 0.219 | **0.010** |
| TE-9 | **-10.5** | **-10.0** | **-7.87** |
| | **0.040** | **0.052** | **0.098** |
| TE-10 | 0.760 | 1.72 | 1.56 |
| | 0.884 | 0.745 | 0.747 |
| Intercept | 5.15 | 4.49 | **7.91** |
| | 0.175 | 0.243 | **0.041** |
| delta \$mtrl/unit | -0.0001 | -0.0001 | -0.0001 |
| | 0.758 | 0.839 | 0.796 |
| delta sales vol | 0.00004 | 0.00005 | 0.00001 |
| | 0.606 | 0.485 | 0.905 |
| % prod add | | -8.80 | 7.64 |
| | | 0.343 | 0.473 |
| (% prod add)$^2$ | | | **-137.1** |
| | | | **-0.015** |
| % updates entering | -0.062 | 1.92 | 1.42 |
| | 0.985 | 0.624 | 0.692 |
| $R^2$ | 0.539 | 0.553 | 0.639 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 22**
**Model 4a – Delta Indirect Cost – lag 1**

| **Hierarchical Regression: Model 4a DV = Delta Indirect Cost Time lag = 1** | | | |
|---|---|---|---|
| BE-1 | -2.05 | -4.28 | -8.22 |
| | 0.675 | 0.395 | 0.100 |
| BE-2 | -1.97 | 1.01 | -4.37 |
| | 0.641 | 0.826 | 0.357 |
| BE-3 | -1.25 | -1.05 | -4.19 |
| | 0.748 | 0.783 | 0.267 |
| Intercept | 2.55 | 2.25 | 1.94 |
| | 0.391 | 0.442 | 0.475 |
| delta $mtrl/unit | 0.0003 | 0.0004 | 0.0003 |
| | 0.354 | 0.270 | 0.293 |
| delta sales vol | **0.0002** | **0.0002** | **0.0001** |
| | **0.010** | **0.012** | **0.040** |
| % prod add | | 21.8 | -3.90 |
| | | 0.138 | 0.816 |
| (% prod add)$^2$ | | | **163.9** |
| | | | **0.016** |
| % updates entering | -1.09 | -4.99 | 0.252 |
| | 0.834 | 0.384 | 0.964 |
| $R^2$ | 0.208 | 0.262 | 0.389 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 23**
**Model 5a – Delta Indirect Cost – lag 1**

| **Hierarchical Regression: Model 5A DV = Delta Indirect Cost Time lag = 1** | | | |
|---|---|---|---|
| TE-1 | -5.70 | -4.83 | -4.83 |
| | 0.263 | 0.312 | 0.319 |
| TE-2 | 2.96 | 2.57 | 2.13 |
| | 0.558 | 0.586 | 0.659 |
| TE-3 | **-18.0** | **-16.7** | **-17.2** |
| | **0.006** | **0.007** | **0.007** |
| TE-4 | -1.69 | -2.26 | -2.29 |
| | 0.755 | 0.658 | 0.658 |
| TE-5 | -2.20 | -1.15 | -1.03 |
| | 0.663 | 0.808 | 0.829 |
| TE-6 | 4.48 | 5.24 | 5.51 |
| | 0.372 | 0.268 | 0.252 |
| TE-7 | **-10.8** | -6.41 | -7.79 |
| | **0.063** | 0.263 | 0.213 |
| TE-8 | **-8.84** | **-8.39** | **-8.23** |
| | **0.097** | **0.043** | **0.104** |
| TE-9 | -0.687 | 1.92 | 1.70 |
| | 0.894 | 0.699 | 0.737 |
| Intercept | 5.78 | 4.63 | 4.54 |
| | 0.116 | 0.182 | 0.198 |
| delta $mtrl/unit | 0.0005 | 0.0005 | 0.0005 |
| | 0.207 | 0.214 | 0.196 |
| delta sales vol | 0.000005 | 0.00001 | 0.000004 |
| | 0.950 | 0.875 | 0.962 |
| Port Growth | | **14.7** | **16.6** |
| | | **0.038** | **0.036** |
| (Port Growth)$^2$ | | | 9.96 |
| | | | 0.546 |
| % updates entering | 0.954 | -1.39 | -1.33 |
| | 0.779 | 0.680 | 0.696 |
| $R^2$ | 0.569 | 0.636 | 0.642 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 24**
**Insert 5a-delta indirect cost-2**

| **Hierarchical Regression: Model 5a DV = Delta Indirect Cost Time lag = 2** | | | |
|---|---|---|---|
| TE-1 | 2.05 | 3.55 | 3.61 |
| | 0.691 | 0.479 | 0.481 |
| TE-2 | **-15.6** | **-13.3** | **-13.6** |
| | **0.012** | **0.028** | **0.029** |
| TE-3 | -4.39 | -3.10 | -3.04 |
| | 0.392 | 0.570 | 0.546 |
| TE-4 | -4.29 | -1.67 | -1.78 |
| | 0.484 | 0.777 | 0.768 |
| TE-5 | 4.65 | 6.01 | 6.13 |
| | 0.363 | 0.228 | 0.229 |
| TE-6 | -8.86 | -7.48 | -7.26 |
| | 0.118 | 0.169 | 0.192 |
| TE-7 | **-11.1** | **-12.5** | **-13.1** |
| | **0.037** | **0.017** | **0.018** |
| TE-8 | -1.53 | 0.128 | 0.213 |
| | 0.789 | 0.982 | 0.970 |
| Intercept | 5.70 | 4.49 | 4.28 |
| | 0.133 | 0.220 | 0.255 |
| delta $mtrl/unit | -0.0004 | -0.0004 | -0.0004 |
| | 0.312 | 0.304 | 0.325 |
| delta sales vol | 0.00005 | 0.00004 | 0.00004 |
| | 0.540 | 0.562 | 0.548 |
| Port Growth | | **-12.9** | -11.4 |
| | | **0.082** | 0.173 |
| (Port Growth)$^2$ | | | 6.89 |
| | | | 0.678 |
| % updates entering | 2.47 | 4.53 | 4.46 |
| | 0.490 | 0.214 | 0.231 |
| $R^2$ | 0.586 | 0.638 | 0.641 |

BE = Fixed effect for brand
TE = Fixed effect for time

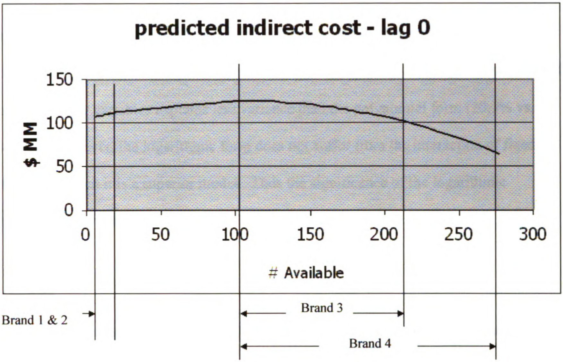
| B term |
|---|
| p-value |

Model 1a uses the number of products available as the operationalization of multiplicity whereas model 4a uses the percentage of products added to the portfolio and model 5a uses the percentage of portfolio growth. All three models use second order polynomials to test the relationship between multiplicity and indirect cost.

Model 1a

The hierarchical regressions for model 1a reveal the coefficient for the linear multiplicity variable is positive and significant at the 0.10 level for the one period prior scenario. The total variance in indirect cost explained by the model is 98.0% with the controls and fixed effects explaining 97.7%. For the no lag scenario both the linear and non-linear terms are positive and significant at the 0.05 level. Graphing this function over the range of the data reveals an inverted U shaped curve (see Figure 12). The variance explained by the controls and fixed effects is 97.4%. The multiplicity variables explain an additional 0.7%.

**Figure 12**
**Hypothesis 4 Model 1a**




To confirm the validity of the shape of the curve each brand was plotted. In this case, the brand level plots revealed two distinct populations; two that increase linearly and thus provide partial support for the hypothesis, and two that decline exponentially.

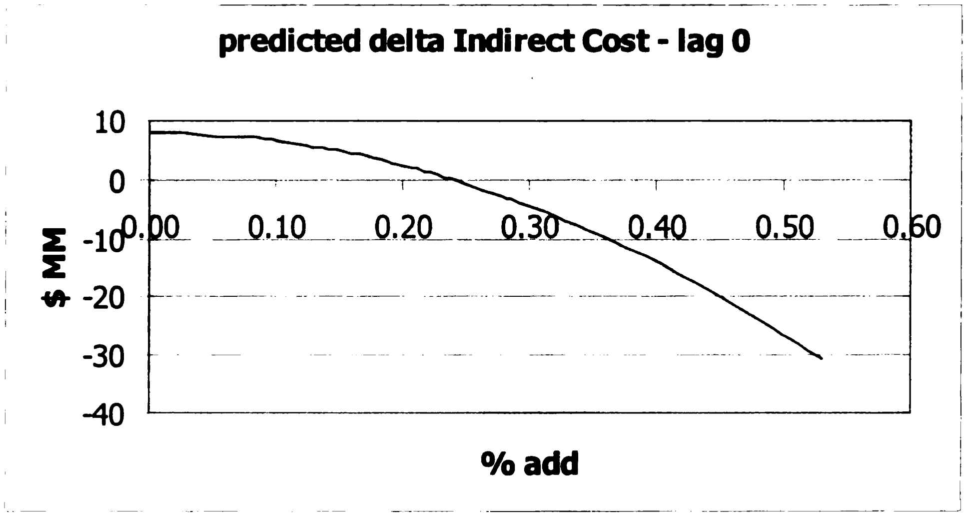
Because the individual plots are likely errant due to their creation using the coefficient from the regression equation that had interacting brand effects, separate regressions were performed on each brand using just the complexity variables. The reduced number of variables was required due to the small number of data points for each brand. The result is that brands 1, 2, and 4 do not have any statistically significant relationships with indirect cost. However, Brand 2shows a nonlinear increase ($B_{lin} = 21.6$, p=0.046 and $B_{nl} = 0.12$,p=0.049).

In the process of addressing the counter intuitive finding shown in Figure 12 a logarithmic function form was investigated. The outcome is that the logarithmic form of the complexity variables explains less variance than the polynomial form (20.9% vs. 24.4%). However, the logarithmic form does not suffer from the interaction of fixed effects. As such it is a superior model. Thus the significance of the logarithmic relationship provides full support for the hypothesis.

Model 4a

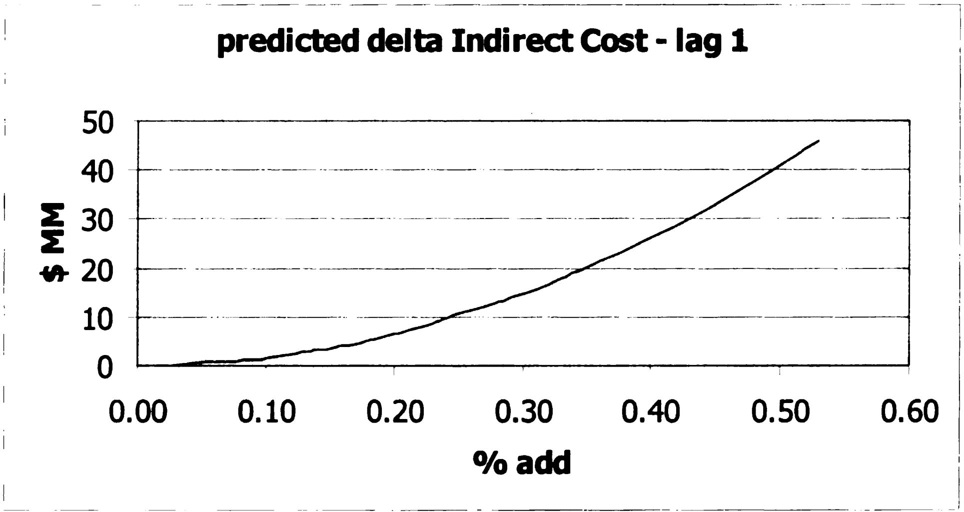
The hierarchical regressions for model 4a reveal the coefficient for the non-linear multiplicity variable is negative and significant at the 0.05 level for the no lag scenario. Graphing the function over the range of available data reveals a curve that monotonically decreases at an increasing rate (see Figure 13). The fixed effects and controls explain 53.9% of the variance in the change in indirect cost and adding the multiplicity variable increases the total variance explained by 10.0% to 63.9%.

**Figure 13**
**Hypothesis 4 Model 4a – no lag**




The non-linear coefficient for the one period lag scenario is positive and significant at the 0.05 level resulting in a curve that increases at an increasing rate monotonically (see Figure 14). The total variance explained by the multiplicity variables is 3.9% whereas the controls and fixed effects explain 20.8%.

**Figure 14**
**Hypothesis 4 Model 4a – lag 1**




Model 5a

The hierarchical regressions for model 5a reveal the coefficient for the linear multiplicity variable is positive and significant at the 0.05 level for the one period lag scenario and negative and significant at the 0.10 level in the two period scenario. The model explains similar amounts of variance in each case with the multiplicity variables explaining 7.3% of variance beyond the controls in the one period lag scenario and 5.5% in the two period lag scenario. The total variance explained is 64.2% and 64.1% respectively.

Summary

The static model, model 1a, provides partial support for the hypothesis in the no lag and one period prior scenarios. The dynamic models, 4a and 5a, provide mixed results. In the one period lag scenario they provide partial support. However, model 4a indicates a decline in the no lag scenario where an increase is hypothesized and model 5a indicates the same in the two period lag scenario.

### 5.5 Hypothesis 5

Hypothesis 5 states that direct cost will decrease at a decreasing rate with increasing levels of similarity. Three operationalizations of similarity were used to create models describing the impact of multiplicity on warranty cost: 1) the percentage of updated products in the portfolio, 2) the degree of age diversification of products, and 3) percentage of products entering the portfolio in a given period that are updates. Direct cost and the change in direct cost were regressed upon the independent and control variables with and without lagged effects.

Model 2a uses the percentage of updated products in the portfolio as the operationalization of similarity whereas model 3a uses the degree of age diversification of products in the portfolio and model 6a uses the percentage of products entering the portfolio that are updates. Models 2a and 3a use second order polynomials to test the relationship between similarity and direct cost whereas model 6a uses only a linear term. The lack of a second order term for model 6a is attributable to collinearity constraints.

None of the models revealed a relationship between similarity and direct cost or changes in direct cost. In the case of model 6a, which uses the percentage of updated products entering the portfolio as the operationalization of similarity, power is nearly zero. This could be the reason why a relationship was not detected.

Summary

No significant relationships were identified using either the static or dynamic models.

### 5.6 Hypothesis 6

Hypothesis 6 states that sales volume will increase at a decreasing rate with increasing levels of multiplicity. Three operationalizations of multiplicity were used to create models describing the impact of multiplicity on volume: 1) the number of products in the portfolio, 2) the percentage of products added to the portfolio in a given period, and 3) percentage of portfolio growth. Sales volume and change in sales volume were regressed on the independent and control variables with and without lagged effects. Tables 25 – 28 display the hierarchical regression results for the models with significant coefficients for the multiplicity variables.

**Table 25**
**Model 1b – Sales Volume – no lag**

| **Hierarchical Regression: Model 1b DV = Sales Volume Time lag = 0** | | | |
|---|---|---|---|
| BE-1 | **232736** | **230648** | **236556** |
| | **<0.001** | **<0.001** | **<0.001** |
| BE-2 | **-24911** | **26767** | **75559** |
| | **0.020** | **0.039** | **0.029** |
| BE-3 | -16206 | **35720** | **37047** |
| | 0.219 | **0.014** | **0.019** |
| Intercept | **30704** | 9968 | 311.9 |
| | **<0.001** | 0.150 | 0.973 |
| $mtrl/unit | 0.805 | 0.849 | 0.562 |
| | 0.635 | 0.513 | 0.662 |
| # prod avail | | **357.1** | **645.1** |
| | | **<0.001** | **0.002** |
| # prod avail$^2$ | | | -1.85 |
| | | | 0.123 |
| % update | -89672 | **-113594** | **-123726** |
| | 0.183 | **0.031** | **0.018** |
| % diversified | -65011 | -39865 | 9956 |
| | 0.587 | 0.663 | 0.917 |
| $R^2$ | 0.973 | 0.985 | 0.986 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 26**
**Model 1b – Sales Volume – lag 1**

| Hierarchical Regression: Model 1b DV = Sales Volume Time lag = 1 | | | |
|---|---|---|---|
| BE-1 | **228303** | **22954** | **239101** |
| | **<0.001** | **<0.001** | **<0.001** |
| BE-2 | **-22837** | 9850 | 42489 |
| | **0.009** | 0.546 | 0.302 |
| BE-3 | -15162 | 23755 | 56408 |
| | 0.655 | 0.190 | 0.180 |
| Intercept | **34542** | **19412** | **13763.0** |
| | **<0.001** | **0.031** | **0.210** |
| $mtrl/unit | 0.235 | 0.155 | 0.142 |
| | 0.884 | 0.915 | 0.923 |
| # prod avail | | **268.8** | **450.7** |
| | | **0.006** | **0.055** |
| # prod avail$^2$ | | | -1.40 |
| | | | 0.385 |
| % update | -17319 | -37473 | -50954 |
| | 0.770 | 0.488 | 0.368 |
| % diversified | -24022 | -19765 | -10316 |
| | 0.828 | 0.843 | 0.919 |
| $R^2$ | 0.978 | 0.983 | 0.983 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 27**
**Model 4b – Delta Sales Volume – no lag**

| Hierarchical Regression: Model 4b DV = Delta Sales Volume Time lag = 0 | | | |
|---|---|---|---|
| TE-1 | -4653 | -4520 | -6463 |
| | 0.691 | 0.698 | 0.577 |
| TE-2 | -8750 | -11176 | -8639 |
| | 0.460 | 0.352 | 0.471 |
| TE-3 | 11414 | 9872 | 5714 |
| | 0.328 | 0.398 | 0.631 |
| TE-4 | **-54149** | **-56763** | **-53520** |
| | **<0.001** | **<0.001** | **<0.001** |
| TE-5 | 2036 | 1522 | 1258 |
| | 0.858 | 0.893 | 0.911 |
| TE-6 | -4177 | -4883 | -4376 |
| | 0.716 | 0.670 | 0.699 |
| TE-7 | 5067 | 3840 | 2733 |
| | 0.660 | 0.739 | 0.810 |
| TE-8 | **-44771** | **-45489** | **-45386** |
| | **0.001** | **0.001** | **0.001** |
| TE-9 | 2730 | 1233 | 3862.0 |
| | 0.811 | 0.914 | 0.736 |
| TE-10 | -14903 | -16844 | -16046 |
| | 0.206 | 0.157 | 0.173 |
| TE-11 | 12680 | **13982** | **17350** |
| | 0.134 | **0.103** | **0.052** |
| Intercept | **-2.47** | **-2.48** | **-2.4** |
| | **0.005** | **0.005** | **0.007** |
| % prod add | | 23481 | **42686** |
| | | 0.261 | **0.095** |
| (% prod add)$^2$ | | | -171685 |
| | | | 0.187 |
| % updates entering | 2383 | -3007 | -3455 |
| | 0.754 | 0.737 | 0.696 |
| $R^2$ | 0.555 | 0.574 | 0.599 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

**Table 28**
**Model 5b – Delta Sales Volume – lag 1**

| **Hierarchical Regression: Model 5b DV = Delta Sales Volume Time lag = 1** | | | |
|---|---|---|---|
| TE-1 | -5685 | -5912 | -5283 |
| | 0.652 | 0.646 | 0.671 |
| TE-2 | 6230 | 6324 | 2618 |
| | 0.621 | 0.622 | 0.835 |
| TE-3 | **-40928** | **-41227** | **-40624.0** |
| | **0.004** | **0.004** | **0.004** |
| TE-4 | 11023 | 11157 | 9782 |
| | 0.415 | 0.418 | 0.463 |
| TE-5 | -3534 | -3813 | -2611 |
| | 0.779 | 0.768 | 0.834 |
| TE-6 | 5295 | 5077 | 6434 |
| | 0.671 | 0.690 | 0.601 |
| TE-7 | **-32953** | **-34100** | **-40177** |
| | **0.014** | **0.020** | **0.007** |
| TE-8 | 7261 | 7123 | 7460 |
| | 0.576 | 0.590 | 0.559 |
| TE-9 | -12328 | -13016 | -13234 |
| | 0.335 | 0.332 | 0.308 |
| Intercept | 9664 | 9961 | 8243 |
| | 0.279 | 0.279 | 0.355 |
| delta $mtrl/unit | 1.46 | 1.47 | **1.53** |
| | 0.117 | 0.122 | **0.099** |
| Port Growth | | -3989 | 10319 |
| | | 0.829 | 0.601 |
| $(\text{Port Growth})^2$ | | | **69300** |
| | | | **0.095** |
| % updates entering | 7048 | 7674 | 7279 |
| | 0.406 | 0.400 | 0.408 |
| $R^2$ | 0.505 | 0.506 | 0.557 |

BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

Model 1a uses the number of products available as the operationalization of multiplicity whereas model 4a uses the percentage of products added to the portfolio and model 5a uses the percentage of portfolio growth. All three models use second order polynomials to test the relationship between multiplicity and sales volume.

<u>Model 1b</u>

The hierarchical regressions for model 1b reveal the coefficient for the linear multiplicity variable to be positive and significant at the 0.05 level for the no lag and one period lag scenarios. Thus the indication is an increase in units sold with increasing levels of multiplicity. The fixed effects and controls explain 97.3% of the variance in the volume for the no lag scenario and 97.8% for the one period lag scenario. Adding the multiplicity variable brings the total variance explained by the model to 98.6% and 98.3% respectively.

<u>Model 4b</u>

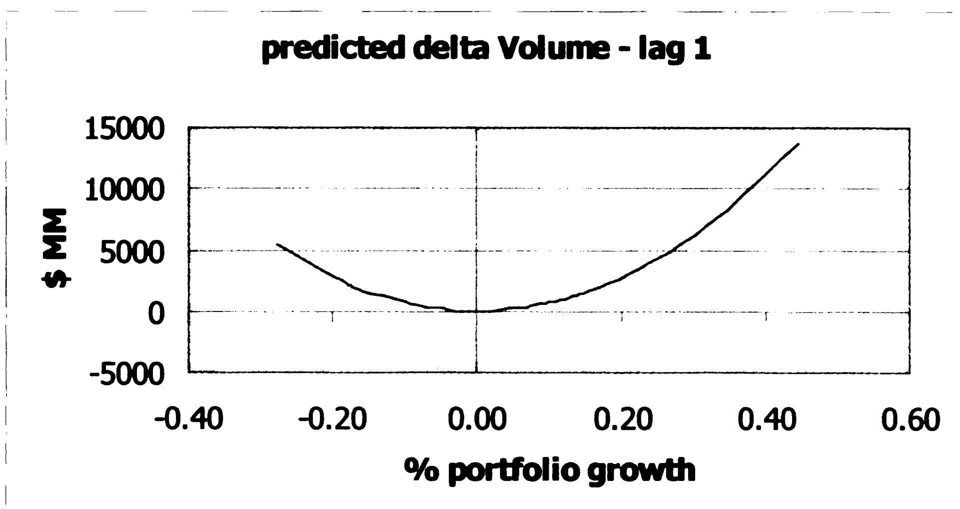
The hierarchical regressions for model 4b reveal the coefficient for the linear multiplicity variable to be positive and significant at the 0.10 level for the no lag scenario. Thus the indication is an increase in units sold with increasing levels of multiplicity. The fixed effects and controls explain 55.5% of the variance and adding the multiplicity variable brings the total variance explained by the model to 59.8%.

Model 5b

The hierarchical regressions for model 5b reveal the coefficient for the non-linear multiplicity variable to be significant and positive at the 0.10 level for the one period lag scenario. The total variance in the change in volume explained by the model is 55.7% with the controls and fixed effects explaining 50.5%. Graphing the significant multiplicity variable over the range of the data reveals a U shaped curve (see Figure 15).

To confirm the validity of the shape of the curve each brand was checked. If each brand manifests the same general pattern, then the confidence can be placed in the curve. However, if plots of the individual brands manifest different patterns, then the result is an interaction of brand effects. In this case, the shape of the curves for each brand are consistent with the curve shown in Figure 15.

**Figure 15**
**Hypothesis 6 Model 5b**



Summary

Model 1b provides partial support for the hypothesis in the no lag and one period lag scenarios. Models 4a and 5a provide partial support in the no lag and one period lag scenarios respectively.

### 5.7 Hypothesis 7

Hypothesis 7 states that sales volume will not be impacted by similarity. Three operationalizations of similarity were used to create models describing the impact of multiplicity on warranty cost: 1) the percentage of updated products in the portfolio, 2) the degree of age diversification of products, and 3) percentage of products entering the portfolio in a given period that are updates. Sales volume and the change in sales volume were regressed on the independent and control variables with and without lagged effects. Table 29 displays the hierarchical regression results for the model with a significant coefficient for a similarity variable.

Model 2a uses the percentage of updated products in the portfolio as the operationalization of similarity whereas model 3a uses the degree of age diversification of products in the portfolio and model 6a uses the percentage of products entering the portfolio that are updates. Models 2a and 3a use second order polynomials to test the relationship between similarity and direct cost whereas model 6a uses only a linear term. The lack of a second order term for model 6a is attributable to collinearity constraints.

**Table 29**
**Model 2b – Sales Volume – no lag**

| Hierarchical Regression: Model 2b DV = Volume Time lag = 0 | | | |
|---|---|---|---|
| BE-1 | **215236** | **224044** | **223208** |
| | **<0.001** | **<0.001** | **<0.001** |
| BE-2 | **20217** | **24693** | **17792** |
| | **0.097** | **0.037** | **0.094** |
| BE-3 | **34413** | **35260** | **28106** |
| | **0.022** | **0.014** | **0.029** |
| Intercept | **15589** | **11045** | **22066** |
| | **0.017** | **0.086** | **0.002** |
| \$mtrl/unit | 0.227 | 0.878 | 0.923 |
| | 0.862 | 0.494 | 0.418 |
| # prod avail | **340.2** | **358.7** | **330.2** |
| | **<0.001** | **<0.001** | **<0.001** |
| % update | | **-104432** | 31796 |
| | | **0.028** | 0.582 |
| % update$^2$ | | | **-1334775** |
| | | | **0.002** |
| $R^2$ | 0.982 | 0.985 | 0.988 |

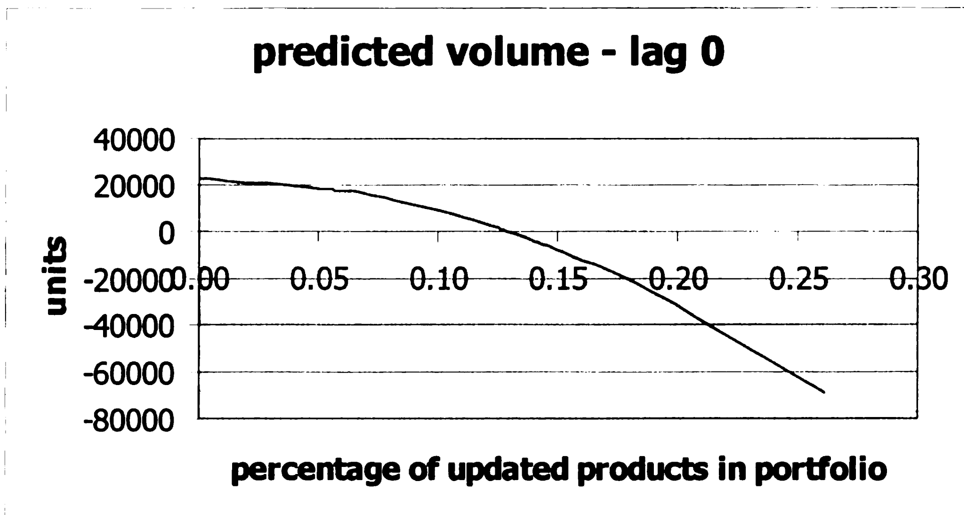
BE = Fixed effect for brand
TE = Fixed effect for time

| B term |
|---|
| p-value |

Model 2b

The hierarchical regressions for model 2b reveal the coefficient for the non-linear multiplicity variable to be negative and significant the 0.05 level for the no lag scenario. The total variance in the change in volume explained by the model is 98.8% with the controls and fixed effects explaining 98.2%. Graphing this function over the range of the data reveals a monotonic curve that decreases at an increasing rate (see Figure 16).

**Figure 16**
**Hypothesis 7 Model 2b**




Models 3b and 6b

The hierarchical regressions using models 3b and 6b failed to detect a significant (<0.10) relationship between similarity and volume or change in volume; model 3b has sufficient power (>0.80), but model 6b has virtually no power.

Summary

The hypothesis is supported with both the static and dynamic models in all scenarios except the no lag scenario of model 2b where a declining relationship was found.

# 6.0 Discussion

## 6.1 Introduction

This chapter discusses and interprets the findings highlighted in the prior chapters. It provides an overview of the hypotheses and whether they are supported as well as an interpretation of the findings on both a global level and by hypothesis.

Table 30 provides an overview of the hypothesized relationships studied and whether support for them was found. A review of the table reveals that there is at least partial support for six of the seven hypotheses. In some cases there is conflicting support; findings that are both consistent and counter to the hypothesized relationship. These findings are discussed below in hypothesis specific sections. A review of the table also reveals that dynamic models explain more instances of complexity's impact on supply chain outcomes (warranty, inventory, etc.) than static models. Within the dynamic models, the percentage of growth in the portfolio appears to have more explanatory power than the percentage of the portfolio comprised of recent additions. These observations are elaborated upon below.

**Table 30**
**Summary of Findings**

| Dimension | Category | Model | Variables | lag -1 | lag 0 | lag 1 | lag 2 |
|---|---|---|---|---|---|---|---|
| | | | | Warranty - H1 | | | |
| Multiplicity | Static | Model 1a | # avail + # avail^2 + % divsfid + % updt + mtls + vol | | S | N | N |
| Multiplicity | Dynamic | Model 4a | % add + % add^2 + % updt ent + dlta mtls + delta vol | | O | P | N |
| Multiplicity | Dynamic | Model 5a | % growth + % growth^2 + % updt ent + delta mtls + delta vo | | P | N | PO |
| | | | | Inventory - H2 | | | |
| Multiplicity | Static | Model 1a | # avail + # avail^2 + % divsfid + % updt + mtls + vol | N | N | N | N |
| Multiplicity | Dynamic | Model 4a | % add + % add^2 + % updt ent + dlta mtls + delta vol | N | N | N | S |
| Multiplicity | Dynamic | Model 5a | % growth + % growth^2 + % updt ent + delta mtls + delta vo | N | P | N | S |
| | | | | Direct Cost - H3 | | | |
| Multiplicity | Static | Model 1a | # avail + # avail^2 + % divsfid + % updt + mtls + vol | | N | N | N |
| Multiplicity | Dynamic | Model 4a | % add + % add^2 + % updt ent + dlta mtls + delta vol | | PO | N | N |
| Multiplicity | Dynamic | Model 5a | % growth + % growth^2 + % updt ent + delta mtls + delta vo | | PO | S | N |
| | | | | Indirect Cost - H4 | | | |
| Multiplicity | Static | Model 1a | # avail + # avail^2 + % divsfid + % updt + mtls + vol | P | P | N | N |
| Multiplicity | Dynamic | Model 4a | % add + % add^2 + % updt ent + dlta mtls + delta vol | N | O | P | N |
| Multiplicity | Dynamic | Model 5a | % growth + % growth^2 + % updt ent + delta mtls + delta vo | N | N | P | PO |
| | | | | Direct Cost - H5 | | | |
| Similarity | Static | Model 2a | % updt + % updt^2 + # avail + mtls + vol | | N | N | N |
| Similarity | Static | Model 3a | % divsfid + % divsfid^2 + # avail + mtls + vol | | N | N | N |
| Similarity | Dynamic | Model 6a | % updt ent + % prod add + delta mtls + delta vol | | N | N | N |
| | | | | Volume - H6 | | | |
| Multiplicity | Static | Model 1b | # avail + # avail^2 + % divsfid + % updt + mtls | | P | P | N |
| Multiplicity | Dynamic | Model 4b | % add + % add^2 + % updt ent + delta mtls | | P | N | N |
| Multiplicity | Dynamic | Model 5b | % growth + % growth^2 + % updt ent + delta mtls | | N | P | N |
| | | | | Volume - H7 | | | |
| Similarity | Static | Model 2b | % updt + % updt^2 + # avail + mtls | | N | S | S |
| Similarity | Static | Model 3b | % divsfid + % divsfid^2 + # avail + mtls | | S | S | S |
| Similarity | Dynamic | Model 6b | % updt ent + % prod add + delta mtls | | S | S | S |

S = Support
N = No Support
P = Partial Support
O = Opposite

## 6.2 Interpretations and explanations

### 6.21 High level interpretations

There are two categories of models that were created to test the hypotheses set forth in this research project: static and dynamic. Between these two types of models, the complexity variables in the dynamic models have more explanatory power. They predict a greater number of outcomes and they provide a greater increase in explained variance over the control variables (about 10% on average compared to about 5% for the static models). This implies that the study company has systems in place that readily adapt to increases in product portfolio complexity and that these systems effectively mitigate the longer term impacts. Stated another way, the study company reacts to changes in complexity levels and begins to manage it effectively, rather than having in place a system which accommodates complexity changes.

This implication is interesting in that contacts at the study firm do not believe complexity is well managed. This perspective may be a result of the business planning process used at the study company. The study company has for decades performed more business planning and monitoring of progress toward realizing the plan than most other firms. This planning process exposes costs and managers are encouraged to address those that rise unexpectedly or too rapidly. The planning process also creates an informal reward system by providing visibility of managers who effectively manage / reduce costs under their purview to senior management. This planning process may be what is driving the response to changes in product portfolio complexity and these responses may include the creation and evolution of systems to effectively manage the change.

An alternative explanation for why static models do not have as much explanatory power is that the study firm simply may have large amounts of untapped capacity in production, production support, and development. While capacity utilization was not provided, the study company continually monitors headcount and willingly reduces it to ensure it is at appropriate levels as evidenced by articles in the popular press. Hence it seems unlikely that spare capacity is the source of the capability of adapting to changing levels of product portfolio complexity over time.

The multiplicity models within the set of dynamic models use two different operationalizations of product portfolio complexity; percentage of portfolio growth and percentage of the portfolio added in the period. The fundamental difference between the two models being that the 'percent growth' variable accounts for the products that exit the portfolio. A review of Table 30 reveals that the growth measure explains significant amounts of variance in a greater number of outcome variables. Additionally, it results in relationships consistent with those hypothesized more often than the 'percent add' measure. Each model explains about the same amount of variance beyond the control variables. Thus the models based upon net portfolio growth are better than those based upon portfolio additions and the model focused on net portfolio growth is better than the model focused on portfolio additions.

This finding makes logical sense. The outcomes that are considered in this study (e.g. warranty cost) are more dependent on the net portfolio size. Additions to the portfolio have impacts, but reductions also have impacts that when accounted for provide meaningful information. Possibly, the information that the net portfolio growth captures is utilization changes.

6.22 Hypothesis 1

The static model for predicting warranty, which uses the number of products available in the portfolio as the operationalization of multiplicity, shows a decrease in warranty cost at an increasing rate. However, this initial result must be set aside as it is an artifact of an interaction of brand effects; this is discussed in greater detail in section 5.2. As a result of discovering the interaction of brand effects, additional analyses were performed. These analyses included investigating a logarithmic relationship between the number of products in the portfolio and warranty cost. It is the significance of the coefficient for the logarithmic multiplicity variable that provides support for the hypothesis that warranty costs will grow at a decreasing rate.

The presence of a curtailment on the rate of increase in warranty cost may be attributable to increases in learning; learning being reflected in better quality as measured by warranty cost. The results, in conjunction with a post hoc regression of warranty cost on similarity (similarity variables were nonsignificant), suggest that greater learning occurs with greater variety rather than greater focus. Thus, it is better to expose a worker to a variety of assembly operations rather than let her perfect a single operation for the purpose of maximizing quality improvement. This finding is consistent with the principle of absorptive capacity (Cohen & Levinthal, 1990) which indicates that exposing a worker to greater variety leads to more situations where learning can take place and more contexts into which the principles learned can be applied and refined.

Given that the increase in multiplicity accentuates socialization (Linderman, Schroeder, Zaheer, Leidtke, & Choo, 2004), Nonaka's (1994) spiral of knowledge creation offers insight into the mechanism by which greater multiplicity can curtail warranty cost. Nonaka states that the spiral containes four steps: socialization, combination, externalization, and internalization. Exposing the worker to a larger number of products provides more reasons to communicate with other workers. At the factory floor level, working on several products may lift the worker's focus from a very narrow task to something more general and hence may be the catalyst for conversations leading to embarkation upon the knowledge spiral. In the context of engineering design, increases in multiplicity may be the catalyst for pushing an engineer out of a silo mentality. Interacting with peers from other product lines increases opportunities to pick up new concepts and combine them with their existing knowledge base. Hence increasing multiplicity facilitates the spiral of knowledge creation, which in turn accelerates learning, which leads to improved quality as reflected by a decrease in warranty cost.

This finding may initially appear contrary to TPF, which suggests that learning is the result of better utilization through scale. However, learning through increases in scope may actually be the best way to increase resource utilization. Considering resources to include the human capital of the firm, accessing it – utilizing it – leads to improved performance. It may even lead to improved utilization of the physical assets.

The dynamic models tell a slightly different story than the static model. Model 4a, which uses the percentage of the portfolio added in the period as the operationalization of multiplicity, shows a nonlinear decline in warranty costs in period zero followed by a nonlinear increase the next quarter. The decrease in period zero may be an artifact since an analysis of the product release dates revealed that most often products are introduced toward the end of the quarter. Since the focus of the model is change in warranty cost, there may not be enough time for changes in multiplicity to impact the dependent variable. Thus the one period lag scenario lagged effect is probably more reliable as there is full quarter where each product has the chance to accrue a warranty claim. The increase found in the one period lag scenario is consistent with the finding of the static model and partially supports the hypothesis.

6.23 Hypothesis 2

Three models were used to test hypothesis two; 1a, 4a, and 5a. Respectively they use the number of products available in the portfolio, the percentage of the portfolio added in the period, and the percentage growth of the portfolio as the operationalizations of multiplicity. The models constructed to test hypothesis two generally show support for the hypothesis. The results of the models constructed in this study reveal that inventory investment grows with increased multiplicity thereby providing support to Fisher et al. (1999). Further more this growth follows the polynomial relationship put forward by Manne (1958) and Wagner & Whitin (1958) and conforms to the variance pooling properties suggested by the Theory of Performance Frontiers (Schmenner & Swink, 1998).

Model 1a, the static model, did not detect a significant relationship with inventory investment. There are a couple potential explanations for this phenomenon. This finding could result if several products are constructed of the same set of components in a build or assemble to order environment since these environments typically result in less inventory build up than make to stock environments. However, this would be partially controlled for by the similarity variable which in the model. The study company operates in a quasi build / assemble to order environment. Their objective is to build to order, but at times finished goods inventory is created proactively or partial units constructed and then finished to order by adding various options after an order is received. Thus there will be changes across time and these should be detected. The quasi nature of the environment suggests that there may be other variables that are masking the relationship between multiplicity and inventory; potential variables include presence of marketing campaigns or the influence of incentive systems. However, even though masked, if there were sufficient power, the effect might be detected. Low power, which is nearly zero in this case, is the most likely explanation for the finding.

However, the dynamic models did detect and explain changes to inventory investment. The model that operationalizes multiplicity using the portfolio growth finds an increasing rate of increase in the period in which the portfolio size is changed. This may be attributable to a build up to ensure high fill rates in case demand takes off faster than expected. Two periods later inventory increases linearly with portfolio growth. This relationship provides partial support for the hypotheses in that the data could be from a location on the growth curve that is relatively flat and hence detected by the model as a linear term. A similar relationship is found using the percentage of products added to the portfolio in the same two period lag scenario. However, in this instance, if the criterion for significance is relaxed, the nonlinear term becomes meaningful and suggests a declining rate of increase as hypothesized. Alternatively, inventory growth could be curtailed as forecasting improves with increased amounts of historical information and component lead times shorten. Together these will have the effect of straightening the growth curve.

6.24 Hypothesis 3

The same three models that were used to test hypothesis two were also used to test hypothesis three; 1a, 4a, and 5a.

Model 1a, the static model, did not detect a significant relationship between multiplicity and direct cost. Besides being attributable to a genuinely null result, the result could be attributable to low power, bad data, or a bad measure. Insufficient power results in the inability to detect statistically significant relationships. However, power is not an issue in this case since a check of power tables (Cohen et al., 2003) reveals that power is greater than 0.90. The likelihood that the null is an artifact of the cost accounting used by the study firm is low since contacts at the firm indicate the costs are actual and not applications.

The most likely explanation is that the number of products available in the portfolio may not measure multiplicity as effectively as desired. There is a positive correlation (r=.306, p=.04) between the number of products available in the portfolio and the percentage that are updates of prior products that provides evidence for the conclusion that the measure may explain little additional information. The initial conceptualization of the measure assumed that there would be less correlation between the number of updated products and the total number of products, thus providing a cleaner representation of portfolio breadth. For example the 'updated' products may be only nominally different and hence offer little differences in assembly or fabrication. Thus the measure of the number of items available in the portfolio is contaminated by the number of products that are similar to others in the portfolio thus impacting the prediction of direct cost. A better measure may be the number of new products in the portfolio.

The two dynamic models, those using percent add and percent growth as operationalizations of multiplicity show a linear decrease in direct cost in the period that changes are made to the portfolio which is counter to the hypothesis. There is a very practical reason that explains this phenomenon. Contacts at the study company confirm that the direct cost of new products is typically lower than older ones. The implication is that replacing older products with newer simply changes the cost structure. This continual cost reduction is consistent with the reductions seen generally in the technology sector. Since the cost of materials is controlled, this implies there is something else driving the cost reductions.

A different relationship is manifested in the one period lag scenario though. The model using percent growth reveals an increase in direct cost at an increasing rate, thereby providing support for the hypothesis. The growth in cost may be related to requirements for additional learning.

Exposure to an increased number and variety of scenarios increases the capacity to learn. Cohen and Levinthal (1990) refer to this as absorptive capacity. In the context of a manufacturing plant, the knowledge gain associated with an increase in absorptive capacity is translated into increased productivity. However, as additions to the portfolio increase, the capacity to apply this knowledge or even function at a steady state level becomes overwhelmed, productivity diminishes, and a rapid increase in direct cost results. Direct costs rise because the manufacturing infrastructure is being required to perform at a level beyond that which the process or operators and managers can handle. The result is manifested as inventory shortages and forecasting limitations, increased material handling requirements, increased work in process, and an increased number of defects and hence scrap or rework.

The interesting implication is that exceeding the capacity of the human capital leads to declines in the utilization of the physical capital. This leads to the question as to whether TPF is properly specified. The theory as initially proposed focuses on the physical assets. It may be that there are latent and antecedent relationships to people, policies, and other such soft / intangible assets that should be incorporated into the theory. Alternatively, these soft / intangible assets may be simply subject to the same forces causing similar outcomes as those seen in the physical assets of production.

The conclusion that increased multiplicity will lead to increased direct cost supports the application of TPF to this context. TPF suggests that decreased utilization will increase costs. Increases in multiplicity will decrease utilization for reasons discussed in chapter three. Thus the increase in multiplicity leading to increased direct cost provides empirical support for TPF.

The conclusion of this research, that increased multiplicity will lead to increases in direct cost, is also consistent with the scenarios alluded to by Skinner (1974b) and Collins and Schmenner (1993). Skinner (1974b) and Collins and Schmenner (1993) hypothesized that increased focus, be it in manufacturing objectives or processes, is an effective means for improving performance. They assert that when a production process is required to do too many things it bogs down and the overall performance diminishes. This increase in focus is analogous to reduced multiplicity. A survey of the financial performance of commercial laboratories provides additional evidence supporting the benefit of reducing multiplicity (Miller & McConneghy, 1997). The survey reports that laboratories more narrowly focused, those offering a lesser number of services to fewer market segments, have the best financial performance. Thus this research provides empirical support for the work of Skinner (1974a) and Collins and Schmenner (1993).

6.25 Hypothesis 4

The static model, which uses number of products available as the operationalization of multiplicity shows a linear increase in indirect cost in the period prior to products becoming available. However, this finding is suspect due to a brand effect interaction.

Using a natural log function is another means of arriving at the hypothesized relationship. It offers the benefit of not being conformable to an increasing rate of decline. Hence an alternate model using a logarithmic relationship instead of a polynomial was constructed as a part of the additional analyses discussed in section 5.5. This revised model shows a logarithmically increasing cost with increasing multiplicity. The significance of the logarithmic relationship in period zero and the one period lag scenario supports the hypothesis.

Both of the dynamic models, 4a and 5a, show a decline in indirect cost. Model 4a shows a decrease at an increasing rate in period zero where model 5a shows a linear decline in the two period lag scenario. These declines in indirect cost might be attributable to business process transformations or unique aspects of the business models for each brand.

If business process transformation initiatives were carried out they would likely be reflected most dramatically in the category of indirect cost. For example, the installation of an e-procurement system should reduce the purchasing effort required to support a product line. Another example would be the implementation of a product data management or product lifecycle management system reducing engineering costs. However, contacts at the study firm indicated there were no such initiatives during the study period.

If the brands were behaving differently in regards to indirect cost, it would be seen in a brand level analysis. This analysis was carried out and established that each brand manifests the same relationship between multiplicity and indirect cost. Thus this is not an issue in this instance.

The explanation that seems most plausible is that the indirect cost is increased in quarters prior to those examined in this research as engineering and other support staff design and make ready for introduction the forthcoming products. It is entirely reasonable to assume that the time required to perform these activities is greater than the 90 days used in the analysis. Hence these costs are already at an elevated level when the analysis begins and what is detected is a return to normal operational levels. Since the study firm has a six month pattern to their planning process, the elevated level of indirect cost may have caught the attention of managers. The result is that managers then take corrective action by reducing headcount or other means of cost curtailment. This rationale is tentatively supported by articles that appear in the popular press.

6.26 Hypothesis 5

None of the models used to test the hypothesis that increased levels of similarity result in increasingly lower direct costs found any statistically significant relationship. Nor were any of the controls for similarity significant in the models testing multiplicity hypotheses.

There are a couple potential rationales why no relationship was found. The first pertains to power. Insufficient power results in the inability to detect statistically significant relationships. However, power is not an issue in this case. A check of power tables

(Cohen et al., 2003) reveals that power is greater than 0.90 and as such is not likely to be the reason for the null result.

The second rationale is that similarity just does not impact direct cost. However, this logic goes against a long standing widely held and empirically validated belief that increased similarity will impact direct cost. Hence this rationale is not likely valid. In a similar vein, it is possible that the benefit to increased similarity is delayed until some point after the two period lag that this analysis is able to accommodate. This too seems implausible as scale benefits tend to be recognized immediately.

A third rationale is that the similarity measures created do not effectively capture the construct. While this may eventually be proven to be true, the logic used to create them is sound. Furthermore, one of the measures is anchored in the literature and has been empirically validated in other settings (Hitt, Hoskisson, & Kim, 1997).

A fourth rationale is that the null result is an artifact of the cost accounting used by the study firm. For example, if the study firm used an allocation factor rather than collecting actual costs. However, this is unlikely since contacts at the firm have indicated the costs are actuals.

Since none of these explanations can be fully embraced, additional research into the measurement of similarity is required.

6.27 Hypothesis 6

The three models used to test the relationship between multiplicity and volume found positive linear relationships in period zero and the one period lag scenarios. This provides partial support of the hypothesis. Full support requires significance of the nonlinear coefficient for the multiplicity variable. The significance of the nonlinear term may have gone undetected due to reduced power (~ 0.55) in the case of models 1b and 4b which use the number of products available as the operationalizations of multiplicity.

The one period lag scenario for model 5b, which uses the percentage of portfolio growth, reveals a different functional form; a U shaped curve. Hence, as the portfolio either contracts or expands, the number of units sold increases. At first blush this seems counter intuitive. However, given the assumption that the products trimmed from the portfolio are not strong market performers, this relationship makes sense. Sales volume increases as new products are entered into the portfolio, as expected. The explanation for the increase in sales from portfolio reductions requires some additional explanation.

Quelch and Kenny (1994) offer a couple reasons why removing poor performers could also result in increased sales volume: customer confusion, brand dilution, and cannibalization. The excess of choice in one brand can confuse a customer and lead to the selection of a safer 'one size fits all' product offered by a competitor. Another potential reason for increased demand with decreased multiplicity is an improvement in the ability of the sales force to explain the merits of each product to either buyers or channel partners resulting in a focusing of the marketing message. Quelch and Kenny

(1994) indicate that line extensions, which are thematically similar to the updated products in this research, rarely expand category demand. Often they cannibalize the flagship product leading eventually to a reduced brand image and a reduction in the ability to draw customers to the brand.

Quelch and Kenny's explanation that a reduction in portfolio size enables the sales staff to better articulate the merits of the product leads to the variance pooling benefits of TPF. The sales staff are more focused on comparatively fewer products; their efforts are concentrated – their efforts are pooled. It could be argued too that their utilization is improved since there is a greater sales volume for their efforts. Both of these arguments support the application of TPF to the intangible asset of the sales forece.

One insight gained from a review of the models used to test hypothesis six pertains to material cost. The coefficient for material cost per sales unit is significant and positive in model 5b. Since higher materials costs are generally associated with higher sales prices this finding appears to be incongruent with the economic principle that lower prices increase sales volume. However, considering the nature of the product, the variable may serve as a proxy for technological advancement or customer perception of performance. This desire for the latest technology or highest performance is a strong inducement for purchase and is reflected in the positive correlation between materials cost and sales volume. Thus customers assign value to technological or performance superiority and use it as a purchasing guideline. The result is that products perceived as superior achieve greater market success.

6.28 Hypothesis 7

Two models were used to test the hypothesis in the static setting, 2b and 3b. Model 2b uses the percentage of the portfolio comprised of updated products as the operationalization of similarity. This model finds no relationship between similarity and volume in the one and two period lag scenarios. However, it finds that volume declines at an increasing rate with increasing levels of similarity in period 0. There are several rationales that might explain this result.

It may be that buyers are skeptical about the value of products that are perceived as minor variations of older products. Alternatively the buyer may be expecting differences between products and not finding them becomes confused causing the buyer to select a competitor's product. Thus as reported in section 6.26, buyers may be seeking notable technological advances and distinguishable value propositions.

Model 3b uses the degree of diversification as the operationalization of similarity. This model found no relationship to sales volume. Since this model has sufficient power (>0.80), this finding is plausible. However, it is possible that the measure does not effectively measure the similarity construct. While this may eventually be proven to be true, the logic used to create it is sound. Furthermore, the measure is anchored in the literature and has been empirically validated in other settings (Hitt et al., 1997).

The model used to test the hypothesis in the dynamic setting, 6b, uses the percentage of products entering the portfolio that are updates as the operationalization of similarity. Consistent with the hypothesis, there were no significant relationships found. However, power is virtually zero and as such no conclusion should be drawn from the analyses.

Considered in conjunction with the insights reported in section 6.26, the findings in this section point to the importance of the portfolio size and complexion. The regression models indicate that too many products and products too similar to one another are each detrimental to sales volume. Therefore, the most successful portfolio must cover the price and performance points of the market parsimoniously and in a manner that allows differentiation of the products from each other. Conventional wisdom is that there are cost benefits to increased standardization. However, the regression models used to test Hypotheses 7 indicate that sales volume is at risk of curtailment from employing increased levels of standardization. This leads to the conclusion that standardization should be on aspects of the product not discernable to the customer e.g. a windshield wiper motor or vent fan. Hence this research provides some empirical validation of comments made by Closs et al. (2007) about the merits of focusing on customer discernable component commonality and is consistent with Kim and Chhajed's (Kim & Chhajed, 2001) finding that customer perceptions of similarity impact the price the customer is willing to pay.

There are several practical implications related to this finding including the use of product platforms and modularity. Since product platforms are a type of strategy to reduce the multiplicity and most often are beyond consumer perception, they may be very effective strategies for cost effective growth. This research provides some empirical support for incorporating platforms into a portfolio when practical. Product modularity requires more attention to the impact of the module on customer perception. While cost improvements can be captured from increased similarity, sales volume growth may be more difficult to recognize since the modules are often feature oriented or evident to the consumer.

## 7.0 Conclusion

### 7.1 Introduction

This chapter addresses the contributions this research project has made to the academic and practitioner communities. It highlights implications that are the result of the contributions and includes a discussion of limitations to ensure that there is full disclosure around the research and to guide any researchers building on the work. A section on lessons learned is included and the research agenda spawned from this research is articulated. The chapter concludes with a synopsis of the research.

### 7.2 Contributions

This research was executed with the intent of advancing theory for the purpose of impacting the practice of management. This objective was realized by demonstrating the appropriateness of a theoretical perspective and the extension thereof, the establishment of a definition and typology of complexity, and the creation and validation of variables that could be used in decision support tools to aid managers in determining the optimal level of complexity for a portfolio of products.

#### 7.21 Research

This research provides a definition for product and portfolio complexity grounded in the literature of multiple disciplines. This definition and the associated typology that was also developed in this research formally establish that product and portfolio complexity are multidimensional constructs. This research empirically establishes the validity of the multidimensional aspect by demonstrating that two separate dimensions of complexity have differential impacts on various costs and demand.

A significant contribution to the academic community is the demonstration that the Theory of Performance Frontiers (Schmenner and Swink, 1998) is an appropriate theoretical lens through which to view issues pertaining to product portfolio complexity. It is this theoretical perspective that provides the rationale for the formulation of the models developed to explain the various cost and demand outcomes. This leads directly to the identification of the functional form of the relationship between each dimension of complexity investigated over the course of this research project and the various cost and demand outcomes examined.

This research also expanded TPF by demonstrating its relevance to capabilities. These capabilities may construed as intangible assets. They are treated as such in the resource based view of the firm and protected as such by firms such as 3M which have unique manufacturing capabilities. One aspect of capabilities is that they may not be smooth; they may be discontinuous or irregular in shape and yet TPF still seems to be useful.

The nature of the nonlinear relationship between complexity and cost and complexity and demand reveals that an optimum level of complexity exists. This is a contribution in its own right, but is facilitated by another contribution; the operationalizations of similarity and multiplicity.

7.22 Managerial

This research demonstrates that an optimal level of product portfolio complexity does exist and provides to firms an approach for quantifying the most profitable levels considering their own portfolios. Specifically, regression equations established to substantiate the hypotheses above can be combined to form a multilevel model predictive of profitability. This model can be incorporated into a decision support tool to aid managers in making decisions about the portfolio that move the organization closer to maximum profitability. A side benefit of this research is the explication of the relative impacts of design reuse and part count reduction initiatives. Hence the manager receives guidance on where to place engineering emphasis. The overall impact being better managed companies using resources more efficiently.

A further contribution to managers is the identification of factors that influence the profit-complexity curve. Factors that can guide the strategic design of the portfolio were identified and validated. Thus armed with the knowledge provided by this research, managers can design their portfolios for either profit or market share.

## 7.3 Implications

7.31 Theory

The demonstration of the Theory of Performance Frontiers (Schmenner and Swink, 1998) as an appropriate theoretical lens through which to view issues pertaining to product portfolio complexity is a significant implication. Extending TPF into the realm of intangibles is another. This was accomplished through establishing the impact of similarity on sales volume and the various costs examined in this study. The 'percentage of updated products in the portfolio' and 'percentage of diversification' serve as proxies for design reuse; product designs being intangible assets. Thus this research has demonstrated that, consistent with the predictions of TPF, better utilization of these intangible assets results in improved performance. Thus this research has extended the scope of TPF and has by definition been theory building.

Another implication of the validation of TPF as an appropriate theoretical lens through which to view issues pertaining to product portfolio complexity is an improved tie between product and portfolio complexity and the discipline of economics. TPF has its foundations in the neoclassical school of economics and to the extent that it describes microeconomic activity, it is an economic theory. This research established the diminishing returns to investment that TPF predicts. Keynesian economics also predicts a decreasing return to investment. Therefore, a bridge is built to prominent economic theory.

This research provides and empirically validates a new definition of complexity. This allows researchers to re-characterize prior research as examining either multiplicity or similarity and constrain the findings to these discrete dimensions. This will create greater harmony within the existing literature and resolve apparent paradoxes. It will also guide future research in a similar manner when adopted by other researchers.

### 7.32 Operationalizations

The determination of the means by which product portfolio complexity can be quantified is another significant outcome of this research project. The implications of the operationalizations of product portfolio complexity include the ability to incorporate them in decision support models. These models would use the operationalizations of product portfolio complexity to guide managerial decision making; the ramification being more profitable levels of complexity represented in the portfolio.

Firms that embrace the use of the complexity factors validated in this research for the purposes of improving decision making will necessarily reduce wasted effort. Finding the optimal level of complexity will result in higher levels of performance given the inputs. This occurs through the enhanced utilization of resources, as highlighted by TPF. Since resources are more fully and effectively utilized, the result is the consumption of fewer resources. These resources, if they are human, can be redirected to other firms or locations of the economy where the marginal return for their use is higher. Alternatively, they could be redeployed within the organization to focus on activities that lead to a stronger competitive position within the industry. Examples of these activities could be the design of novel features or the improvement of manufacturing processes. If the resources are physical, then green initiatives are forwarded and the overall environment improved by reducing natural resource consumption and producing less pollution.

The validation of the operationalizations of product portfolio complexity leads to tools by which future researchers can study the topic. The operationalizations may provide insight to other researchers for additional ways to conceptualize or operationalize the construct, or may prove useful when employed in other settings by researchers from other disciplines. For example social researchers may use the similarity and multiplicity dichotomy to study the transformation process that occurs in the classrooms of primary schools. They may find that class size does not impact the educational outcome to the extent that homogeneity of student ability does.

## 7.4 Managerial Implications

The managerial implications of this research may be quite broad reaching, but the discussion herein will be constrained to those pertaining to marketing, operations, and procurement. These are the areas where the most immediate implications arise and where application of the insights could most readily be made.

### *Marketing*

The research of Closs et. al. (2008) suggests that the propensity of marketing functions to add products and variants to the portfolio can be detrimental to the organization. The findings of this research confirm that there are deleterious impacts to both operational costs and sales volume to increasing the portfolio size too greatly. There is an inverted U shaped curve with product size on the x-axis and sales volume on the y-axis. For each company there will be a unique optimal size of the portfolio. Since the costs are nonlinear as well, there will be a similar relationship with profit. However, the profit maximum may not be at the same point as volume maximum. Therefore market share strategies may be detrimental to the financial health of the firm. Hence top management needs to understand the role of portfolio breadth in determining market share and profitability since it should play a critical role in maintaining the proper size of the portfolio.

There are also implications for portfolio mix. If this research proves to be generalizable beyond the firm from which the data was drawn, the instruction to marketers is to maintain the portfolio in a perpetual state of 'newness' since new products outperform existing products in terms of sales volume. New products should be regularly introduced in replacement of older products. Cosmetic changes of products from time to time will not be effective in growing sales since the consumers will fail to find differences between products with the result being a decline in sales volume. Hence the portfolio manager needs to ensure that there is an appropriate level of differentiation between products in the portfolio.

*Operations*

This research calls attention to the need for operations managers to effectively manage capacity. The critical issue is not whether capacity is available, but whether utilization is at the right level. Hence the organization could benefit from incorporating asset utilization choices at the time of design. This is the next step beyond design for manufacture in that it additionally considers the existing asset constraints of the organization.

This research suggests that mangers could view their assets as a portfolio. This means that the firm should consider the mix of assets and how well suited it is to the needs of the organization. Assets that are more multi-purpose are likely to be superior to those dedicated to a particular product. Multi-purpose assets can handle a wider assortment of needs and as such utilization should increase. However, at the point where setups begin to constrain the utilization, tooling dedicated to the process should be secured and the multi-purpose asset redeployed. Conversely, this research also suggests that there is little benefit to having several highly similar assets performing the same task.

*Procurement*

There are decisions that are made by managers regularly about whether to internalize or externalize production (an asset). This research indicates there are ramifications to cost, quality, and possibly market share that must be considered. While outsourcing may expose the organization to a different set of performance frontiers which are superior their own, there is the risk that the outsourcing firm will take on too many projects. The ultimate result will be a decline in performance.

The insource / outsource question leads to the matter of supplier selection and evaluation. The contracting firm needs to carefully evaluate the types of products produced and processes employed by the contractor and set limits on contractor growth. Consideration should be given to the quality of the production assets relative to peers and that of the contractor. This is critical since gains in performance will only accrue to better utilization of assets, which is in turn limited by the total amount of assets.

There are implications in this research for employee training. This research suggests it is better to expose employees to a broad array of scenarios than to focus the training on the details of a single scenario. Hence human resources departments should re-craft employee development programs to move employees out of silos. There should be a continual churn of employees from one functional area to another. This continual exposure to new situations leads to better overall performance. Extending this concept to the insource / outsource decision for labor suggests the benefit from exposing employees to a wide variety of settings is a compelling argument for using contract labor. Using workers who are continually exposed to other firms and practices offers the potential to make the greatest progress toward performance goals. The caveat being that the contracting company can protect its own intellectual property.

### 7.5 Limitations

The findings of this research should be interpreted in light of its limitations. The first limitation is the power of the study. Although power is generally greater than 0.80, there are a couple instances where it is lacking that impacted the interpretation of the results. The impact of this is that with greater power the nonsignificant coefficients of the nonlinear terms may have been found to be statistically significant and thereby offer greater support to the hypotheses put forward. More significantly, some of the operationalizations which were not found to be related to the performance outcomes examined in this research may actually be good predictors. This lack of power thus limits the empirical validation of these additional conceptualizations of product portfolio complexity and as such their validity remains unknown.

The data set is from a single firm. Many researchers would characterize this as a limitation due to the inability to be generalized beyond the study company. However, the generalizability of the coefficients is not the primary focus of this research but rather the principles revealed in the results. These principles may be generalizable to firms providing competing products to the same markets, which is a significant market globally. Additionally, the principles might be generalizable to portfolios of similar products; multi-system durable electronic goods. Examples include audio equipment, televisions, imaging and diagnostic equipment, many types of medical devices, telecommunications switches, and the like which collectively represent a significant portion of the global economy. However, whether the findings are generalizable is reserved for future studies. Using this research design is appropriate since a new theoretical perspective and operationalizations were tested and the single firm focus prevents confounds exogenous of the study company from masking the findings.

The use of longitudinal data is a particular strength of this study. The ability to detect changes over time greatly improves the ability to claim causality. However, the three year duration of the study is a limitation. Some of the products represented within the portfolio have life spans beyond three years and as such the impacts on outcomes such as warranty cost my not be fully revealed. There is a possibility that the failure frequency could escalate at a point beyond what is supported by the data. Thus lagged effects may not be fully explicated in this study.

### 7.6 Future research

This dissertation is a portion of a multi-stage research agenda investigating the impact of product and product portfolio complexity on supply chain performance outcomes. Figure 1 provides a graphical overview of the dimensions of product complexity which will, over time, be addressed by fully executing the research agenda. Through the exhaustive execution of this comprehensive research agenda, the limitations and remaining gaps in knowledge will be ameliorated and filled. Mitigations for the limitations and remaining gaps in knowledge are mentioned below. These mitigations should be assumed to be incorporated in the research designs of studies spawned by the research agenda discussed further below.

#### 7.61 Address limitations

There are three notable limitations to the research presented in this dissertation: power, external validity, and longitudinal duration. These can be mitigated by incorporating larger sample sizes, greater variety of subjects, and longer time windows respectively. These mitigations will be employed as appropriate in the studies discussed below.

#### 7.62 Address remaining gaps

Gaps in the academic community's knowledge about product portfolio complexity remain. One is the issue of whether the typology of complexity offered in this research is comprehensive. Although two dimensions were empirically validated, there may be more. Thus establishing or refuting the existence of additional dimensions of product and portfolio complexity remains to be accomplished as does determining how to measure these dimensions should they exist.

Gaps remain in the area of operationalizations. In addition to operationalizing dimensions of complexity not studied in this research, there is a need to find improved measures of complexity. For example, finding a measure better that can capture similarity better than percentage diversified or multiplicity more cleanly than number of products in the portfolio.

There is another gap that is more implicit; the nomological net. Missing in the literature is the relationship between product portfolio complexity and other constructs relating to product design and supply chain management; constructs such as flexibility, agility, design effort, supplier collaboration, customer perception of value, market value of the firm, firm growth, etc. Additionally, the existence and influence of moderating or mediating relationships remains to be established and quantified.

Beyond the more general gaps mentioned above, there are some specific gaps that this research has identified. One pertains to the phenomenon found in the analysis carried out in the evaluation of hypotheses one and four. The phenomenon is the different relationships between multiplicity and warranty or indirect cost. Additional exploration is warranted to uncover reasons for this difference. Are there differences in the supply chains, incentive plans, tools to manage complexity, some aspect of the business model?

Common wisdom is that costs in the high tech sector decline because increased volume amortizes development costs over a larger number of products; once recovered the development cost can be removed from the price of an item. However, this research shows that there are reasons beyond the cost of materials. There is an opportunity to identify these forces and quantify their impact.

A rationale was put forward in chapter six that when knowledge acquisition / application is required that exceeds a threshold point, performance degrades. How to identify that point has not been articulated in the literature of operations management.

### 7.63 Extensions

There are three extensions to this research that could be undertaken. One is to add portfolios of similar types of products such as those from HP, Sun, and Dell. Beyond that is the analysis of other products that are similar; highly engineered, durable, electronic. Medical and laboratory instrumentation are two examples of similar products, but from different markets. Looking more microscopically, another extension is to explore a more detailed level of the data. Research could be undertaken to explore complexity at the component or option level. Lastly, the principles elucidated in this research could be tested in a services environment.

### 7.64 Additional research questions emerging from this study

- What is the relationship between complexity management competencies and supply chain design?

- What is the role of fit between product and supply chain design?
- Does supplier involvement moderate the impact of complexity on product cost?
- What is the role of fit between tangible and intangible assets?
- What factors moderate the relationship between tangible and intangible assets?
- What causes the decline in cost, beyond that explained by volume and materials, in high tech products?
- What is the point of diminishing performance of the human capital?
- What is the role of fit in regards to employee capability and product portfolio complexity?
- What is the best way to operationalize similarity?
- What is the best way to operationalize multiplicity?
- What aspects of a business model are the most critical to enabling the effective management of complexity?

### 7.7 Summation of dissertation

This study enhances the understanding of the relationship between product portfolio complexity and various costs and sales volume by clearly defining the construct, developing a typology, applying the theoretical framework of Theory of Performance Frontiers, developing measures or complexity factors descriptive of the construct, and testing several hypotheses informed by the definition and theoretical perspective.

From a thorough grounding in the literature, product portfolio complexity was defined as the state of possessing a multiplicity of, and relatedness among, products within the portfolio. Product portfolio complexity was empirically established as possessing two dimensions, multiplicity and relatedness, by demonstrating their differential impacts on various costs and demand.

Several measures of multiplicity and similarity, informed by the definition and theoretical perspective, were created. The measures include: the number of products available in the portfolio, the number of products added to the portfolio, number of products exiting the portfolio, revenue per product, products per model, age differential, maximum age, the variance of age among products, age entropy, percentage of the portfolio composed of updates to prior products, the amount of churn for products. Hypotheses which relate these measures to various costs and sales volume were tested by analyzing longitudinal product portfolio and cost data provided by a designer and manufacturer of data processing equipment using panel data regression.

Thus this research fills a portion of the gap in understanding that exists about the relationship between product portfolio complexity and firm performance by providing a theoretically grounded understanding of product portfolio complexity's relationship to cost and sales volume. Further, a typology of complexity is developed, two of its dimensions operationalized, and the Theory of Performance Frontiers extended to intangible assets. Beyond the contributions to the research community is the benefit offered to the business community. Specifically, this research provides a quantitative approach to identifying the most profitable configuration of a product portfolio. Thus the research both advances theory and offers benefit to the practitioner community.

# Appendix

# Static Model Non-Significant Results

| Model | DV | Lag | %dvfd | p | %dvfc^2 | p | #avail | p | #avail^2 | p | %dvsfd | p | %updt | p | %updt^2 | p | mtrls | p | vd | p |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model 1a | Warranty | 1 | | | | | .150 | .241 | -0.001 | .300 | -63.6 | .181 | 7.31 | .739 | | | -.0002 | .827 | 1x10-7 | 0.999 |
| Model 1a | Warranty | 2 | | | | | .035 | .522 | -.001 | .531 | -99.3 | .078 | -8.00 | .704 | | | -.0001 | .855 | .0001 | 0.518 |
| Model 1a | Inventory | -1 | | | | | -.175 | .750 | .0004 | .900 | -308 | .235 | 140.7 | .220 | | | -.003 | .383 | .0001 | 0.804 |
| Model 1a | Inventory | 0 | | | | | .023 | .971 | .0004 | .887 | -132 | .570 | 8.17 | .949 | | | -.004 | .299 | -.00002 | 0.97 |
| Model 1a | Inventory | 1 | | | | | .596 | .313 | -.002 | .582 | -110 | .611 | -210 | .048 | | | -.005 | .189 | -.0001 | 0.902 |
| Model 1a | Inventory | 2 | | | | | .456 | .501 | -.002 | .742 | -5.01 | .986 | -115 | .252 | | | -.002 | .550 | .0003 | .559 |
| Model 1a | Direct Cost | 0 | | | | | -.265 | .682 | .0002 | .948 | 129 | .533 | 128 | .323 | | | .013 | .001 | .002 | .000 |
| Model 1a | Direct Cost | 1 | | | | | .061 | .929 | -.001 | .791 | 196 | .443 | 73.1 | .540 | | | .014 | .002 | .002 | .001 |
| Model 1a | Direct Cost | 2 | | | | | .228 | .762 | -.001 | .813 | 345 | .271 | -39.5 | .742 | | | .012 | .006 | .002 | .002 |
| Model 1a | Indirect Cost | 1 | | | | | .206 | .244 | -.001 | .277 | -.001 | .277 | -103 | .119 | | | 12.4 | .680 | .0003 | .771 |
| Model 1a | Indirect Cost | 2 | | | | | .068 | .724 | -.0005 | .749 | -147 | .075 | .889 | .977 | | | .0002 | .826 | .0001 | .419 |
| Model 1b | Volume | 2 | | | | | 88.9 | .789 | .867 | .735 | 12759 | .925 | 57103 | .207 | | | -2.89 | .085 | | |
| Model 2a | Direct Cost | 0 | | | | | -.252 | .302 | | | | | 77.0 | .637 | 295 | .830 | .013 | .001 | .002 | .000 |
| Model 2a | Direct Cost | 1 | | | | | -.162 | .566 | | | | | 148 | .390 | -848 | .504 | .013 | .002 | .002 | .001 |
| Model 2a | Direct Cost | 2 | | | | | .095 | .780 | | | | | -159 | .369 | 1059 | .413 | .012 | .006 | .002 | .002 |
| Model 2b | Volume | 1 | | | | | 280 | .011 | | | | | -1169 | .987 | -226000 | .665 | -3.35 | .032 | | |
| Model 2b | Volume | 2 | | | | | 185 | .196 | | | | | 40000 | .595 | 113000 | .837 | -2.83 | .081 | | |
| Model 3a | Direct Cost | 0 | 2.92 | .989 | -5580 | .198 | -.178 | .426 | | | | | | | | | .013 | .001 | .002 | .000 |
| Model 3a | Direct Cost | 1 | 83.1 | .726 | -5180 | .251 | -.121 | .663 | | | | | | | | | .013 | .002 | .002 | .001 |
| Model 3a | Direct Cost | 2 | 292 | .355 | -3170 | .508 | .0001 | .999 | | | | | | | | | .012 | .005 | .002 | .001 |
| Model 3b | Volume | 0 | 77200 | .428 | -183000 | .926 | 312 | .001 | | | | | | | | | -2.89 | .063 | | |
| Model 3b | Volume | 1 | 17600 | .963 | 185000 | .923 | 272 | .015 | | | | | | | | | 3.21 | .037 | | |
| Model 3b | Volume | 2 | -18400 | .897 | -385000 | .860 | 215 | .205 | | | | | | | | | -3.02 | .071 | | |

# Dynamic Model Non-Significant Results

| Model | DV | Lag | %add | p | %add^2 | p | %growth | p | %growth^2 | p | %updtent | p | dt mtl | p | dt vol | p |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model 4a | Warranty | 2 | -10.7 | .328 | -.0005 | .494 | | | | | 4.28 | .288 | -.0002 | .621 | .00001 | .809 |
| Model 4a | Inventory | -1 | -76.0 | .175 | .001 | .734 | | | | | 10.7 | .651 | .002 | .185 | .0002 | .541 |
| Model 4a | Inventory | 0 | .524 | .992 | .006 | .055 | | | | | -21.8 | .289 | -.001 | .432 | .0001 | .844 |
| Model 4a | Inventory | 1 | -73.7 | .222 | .003 | .358 | | | | | -10.4 | .639 | .001 | .679 | .001 | .142 |
| Model 4a | Direct Cost | 1 | 80.9 | .429 | .007 | .241 | | | | | -28.8 | .449 | -.005 | .091 | .001 | .029 |
| Model 4a | Indirect Cost | -1 | 15.6 | .277 | -.001 | .542 | | | | | -1.91 | .752 | -.0001 | .829 | .00005 | .598 |
| Model 4a | Indirect Cost | 2 | -19.6 | .209 | .0004 | .726 | | | | | 8.77 | .132 | -.001 | .192 | .00001 | .933 |
| Model 4b | Volume | 1 | 35300 | .333 | -1.120 | .582 | | | | | 1610 | .906 | 1.42 | .177 | | |
| Model 4b | Volume | 2 | -42600 | .315 | -.182 | .953 | | | | | 19800 | .203 | -.745 | .521 | | |
| Model 5a | Inventory | -1 | | | | | -44.4 | .232 | -27.5 | .707 | 4.41 | .048 | .002 | .170 | .0002 | .603 |
| Model 5a | Inventory | 1 | | | | | -37.8 | .310 | -109 | .165 | -19.1 | .364 | .001 | .733 | .001 | .115 |
| Model 5a | Direct Cost | 2 | | | | | -1.19 | .125 | -93.6 | .529 | 22.9 | .585 | .002 | .468 | .001 | .156 |
| Model 5a | Indirect Cost | -1 | | | | | 13.1 | .164 | 13.5 | .463 | -.828 | .887 | -.0001 | .775 | .0001 | .440 |
| Model 5a | Indirect Cost | 0 | | | | | -12.5 | .143 | -22.4 | .211 | 2.25 | .637 | -.0003 | .504 | .00001 | .906 |
| Model 5b | Volume | 0 | | | | | 1210 | .948 | -55500 | .151 | -8440 | .427 | -2.43 | .007 | | |
| Model 5b | Volume | 2 | | | | | -11500 | .667 | -12800 | .807 | 13600 | .354 | -.664 | .567 | | |
| Model 6a | Direct Cost | 0 | -190 | .009 | | | | | | | 19.5 | .492 | .009 | .001 | .002 | .0002 |
| Model 6a | Direct Cost | 1 | 115 | .248 | | | | | | | -24.5 | .522 | -.005 | .078 | .001 | .038 |
| Model 6a | Direct Cost | 2 | -180 | .136 | | | | | | | 40.6 | .366 | .002 | .513 | .001 | .223 |
| Model 6b | Volume | 0 | 3580 | .897 | | | | | | | -5760 | .618 | -2.43 | .008 | | |
| Model 6b | Volume | 1 | 29900 | .385 | | | | | | | 894 | .947 | 1.49 | .150 | | |
| Model 6b | Volume | 2 | -43300 | .276 | | | | | | | 19700 | .190 | -.733 | .510 | | |

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