2008

Volume and Cost Implications of Product Portfolio Complexity

Mark A. Jacobs
University of Dayton, mjacobs1@udayton.edu

1.0 Overview of the research

1.1 Introduction

This monograph 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

Table 1

Continued

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
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

Table 1

Continued

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:

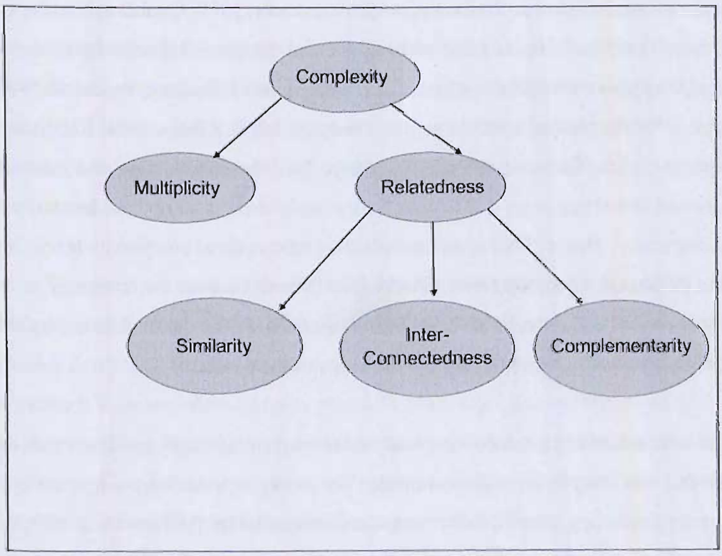
> *Product complexity is a design state resulting from the multiplicity of, and relatedness among, product architectural elements.*

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 monograph 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 followed the time table presented in Table 2.

Table 2

Plan of Work

Activity	**Completion Date**
Frame research	January 1, 2007
Gather data	November 30, 2007
Analyze data	March 31, 2008
Final monograph completed	July 31, 2008