Product Complexity: A Definition and Impacts on Operations

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As evidenced by recent articles in *The Wall Street Journal* (Lawton, 2007) and Forbes (Patton, 2007), there is a growing emphasis on product design resulting in products that are increasingly more differentiated and aimed at more and more narrowly defined market segments. The result is product portfolios manifesting increasing levels of complexity. While adding to the portfolio may enhance revenue, it appears to be at a high cost.

In a recent survey, 57 percent of executives reported that the cost to manage customer orders, procure and inventory materials, and deliver products to end users threatens to undermine operational efficiencies and to consume profits (Hoole, 2006). Product complexity in business supply chains is the primary driver of these costs (Bozarth, Warsing, Flynn, & Flynn, 2007). Case research confirms that many companies are indeed struggling with product complexity decisions (Closs, Jacobs, Swink, & Webb, 2007), and marketing initiatives appear to be a major culprit. Marketers constantly pushing for greater differentiation of their products added 1.7 new products for each product retired (Hoole, 2006). Thus it appears that the challenges presented by product complexity are pervasive and significant to organizations (ATKearney, 2004).

The difficulty for organizations arises because neither complexity nor its impacts on performance are well understood (Fisher & Ittner, 1999b). The mechanisms through which it affects cost, quality, delivery, and flexibility need to be explained (Ramdas, 2003). However, this cannot happen until complexity can be explained theoretically. But, to build theory there must first be a common understanding about the construct of interest (Wacker, 2004). Only then can researchers operationalize it and search for meaningful relationships. In light of this, I develop a definition of complexity below. A sampling of the operations management literature is then presented within the context of the definition. Then, given the definition, an example of how theory can be applied is offered and propositions drawn therefrom.

Definition

The study of product complexity has been hampered by the lack of consensus around 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 investigated several different disciplines to gain a comprehensive understanding of how complexity has been conceptualized to date. These findings are summarized in Table 1. For brevity, the elucidation of these findings will be reserved to other publications (Jacobs & Swink, 2007).

Inspection of Table 1 reveals harmony amongst the uses of the word complexity in the academic literature. These similarities include multiplicity, relatedness, and difficulty of comprehension. Therefore, I propose the following definition of complexity.

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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 & Shoenherr (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 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 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 (1999a)	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

Table 1: Findings on how complexity has been conceptualized to date.

> 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. Ceteris paribus, one product is considered more complex than another if it contains a greater multiplicity of elements or more inter-relationships among its elements than the other. We therefore define product complexity as follows:

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

Multiplicity relates to an enumeration of items. However, as can be seen in Figure 1, relatedness has three dimensions; similarity, interconnectedness, and complementarity. Similarity includes sharing 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 that identified by Ulrich's (1995) slot, bus, and sectional typology. The gist is that there

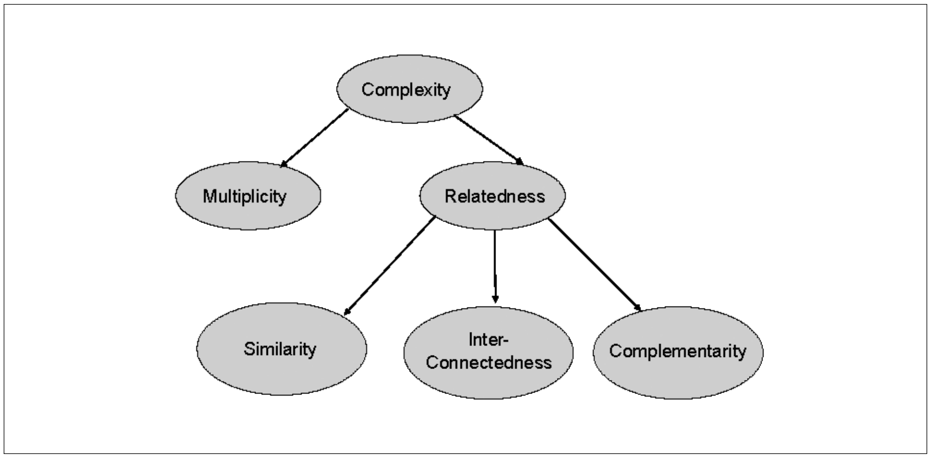

Figure 1: Three dimensions of Relatedness.

is a mechanical connection or the passing of signals between two elements. The interconnectedness of elements also includes logical interconnectedness. 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 intended in the economic sense; an mp3 player and digital music are complements.

The Literature

As presented, product complexity represents a multiplicity of related elements. Systems theory (Boulding, 1956; Simon, 1962) informs us that product complexity can be represented on several levels. My review of the literature finds that these levels include the portfolio of a firm's offerings and the product family, and extend down to the component level of the products within the portfolio.

My view is that the genesis of product complexity resides at 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 at least one becoming a runaway success. There are further forces such as competitive positioning and responses that work to cause firms to offer more products.

The impacts of product complexity on firm operations are explored primarily in three separate research streams: complexity management, measures, and inventory. Inventory is the thread which ties the streams together as much of the management literature looks at effectiveness in reducing inventory levels or costs, and the measures are also focused on improving inventory positions. However, even though elements related to portfolio complexity have been studied since the 1970's, there has yet to emerge a unified framework. Placing the collective work of these scholars into a new context, it becomes apparent that relational complexity has different outcomes than multiplicity complexity. This becomes most evident in the treatments of platforms and modularity within the literature.

The relationship between relatedness and multiplicity complexity was tacitly addressed by Krishnan and Gupta (2001) who found that the benefit to increasing the use of common platforms (relational complexity) was a function of the component costs. They found that increasing platform use was beneficial as long as the unit cost of the component being standardized was not too high relative to alternative suitable components (multiplicity complexity). Others (Krishnan, Singh, & Tirupati, 1999; Sanderson & Uzumeri, 1995) articulate how the use of a common platform can be advantageous to cost-effectively pursuing additional market segments. One interpretation of this work is that there can be increasing returns to decreasing complexity, but that the benefit is bounded by component costs. Therefore the benefit to the relational dimension of complexity may be concave.

A significant body of work has emerged on the topic of modularity—modularity representing an increase in reledness complexity. Modularity enables scale economies (Pine, Victor, & Boynton, 1993), inventory reductions (Fisher, Ramdas, & Ulrich, 1999a; Ramdas & Randall, 2004; Swink & Closs, 2006; Tu, Vonderembse, Ragu-Nathan, & Ragu-Nathan, 2004), engineering efficiencies (Collier, 1981), and improved coordination (Nobeoka & Cusumano, 1997; Sanchez & Mahoney, 1996; Schilling, 2000). However, the benefits are shown analytically to be a function of the cost of the components being standardized (Fisher et al., 1999b; Karmarkar & Kubat, 1987). Empirical research shows that the advantages of modularity can have a positive impact on elements of competitive performance (Jacobs, Droge, Vickery, & Calantone, 2006; Jacobs, Vickery, & Droge, 2007). However, remaining is the need to describe the nature of the functional relationships between the dimensions of complexity and competitive performance.

A logical area for OM researchers to explore in relation to product complexity is inventory. Indeed this is where the primary focus of the operations management literature has been. Most of this research builds on that of Collier (1981) by looking at the impact of variety upon inventory. The first of these was the seminal work of Collier (1982) who demonstrated that as the magnitude of the Degree of Commonality Index (DCI) increased, the safety stock required decreased. Similar works, for example, Baker, Magazine and Nuttle (1986), Gerchak, Magazine and Gamble (1988), McClain, Maxwell, Muckstadt, Thomas, Weiss, and Collier (1984), followed shortly afterward, presenting similar findings. Later, Fisher and Ittner (1999b) explored this topic and found through simulation that the reduction is attributable to risk pooling. Others furthered this stream and clarified the relationship when they found that production volume is a significant driver of the benefit to sharing components (Fisher et al., 1999a). Gerchak and his colleagues have explored impacts of standardizing components on service levels (Gerchak et al., 1988), finding that standardization improves them. Swaminathan and Tayur (1998) chose to look at the problem at a different level. They indirectly address product complexity in their modeling of the benefits of delayed differentiation. They find that the use of vanilla boxes can reduce the cost of supplying variants of computers relative to the make to stock model.

There is a second well-developed stream of literature: measures of complexity. These measures are predominately used to identify opportunities to optimize inventory. Note that these measures have been presented in the context of commonality. However, commonality is just a reduced state of complexity and hence should be viewed as one end of the complexity spectrum. Therefore, these measures assess degrees of complexity.

The first to apply a measure of component complexity (multiplicity) was Roque (1977), who identified the average number of applications per component as a measure of standardization. His suggestion was that resource savings would be realized through an increase in standardization. However, it was Collier's (1981) degree of commonality index (DCI) that proved to be the measure that other scholars built on.

Wacker and Treleven (1986) built upon the DCI by creating indices that captured the degree of complexity across various dimensions, for example, Between Product Constant Commonality Index (BCCI), Total Constant Commonality Index (TCCI), and Within Product Constant Commonality Index (WCCI). Focusing at the component level, these measures account for the degree of complexity across products, the degree of standardization, and how much complexity is present within a product respectively. These measures did prove to be of value in modeling and forecasting the inventory effects from changing the level of component complexity.

There is a second class of measures that has appeared recently in the literature that focuses on the interactions between components or modules. Researchers (Browning, 2001; Eppinger, 2001; Yassine & Braha, 2001) have employed the product structure matrix to visually represent interconnections. A calculation of the percentage of connections (Mac Cormack & Rusnak, 2006) yields the degree of component complexity. Another technique uses a ratio of connections within modules to those between modules to ascertain the degree of product complexity (Gershenson, Prasad, & Allamneni, 1999). Most recently, Fixson (2005) suggests that complexity can be operationalized by creating a two dimensional space with 'number of components' as one axis and 'number of functions provided by the component' as the other. The result is the number of components per function.

A Theoretical Perspective on Product Complexity

There are two theoretical perspectives that offer insights into the effects that product complexity will have on operations. These two theories are the Theory of Performance Frontiers (TPF) (Clark, 1996; Hayes & Pisano, 1996; Schmenner & Swink, 1998; Skinner, 1996) and Transaction Cost Economics (TCE) (Coase, 1937; Williamson, 1981, 1991, 1996, 2002).

The Theory of Performance Frontiers has its basis 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 investment, and that substitution of resources 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." An organization may move its level of performance closer to the asset frontier by revising its policies and procedures in ways that more fully utilize its assets. The resulting increased effectiveness should be reflected by gains in productivity and financial performance (Clark, 1996; Hayes et al., 1996; Schmenner et al., 1998; Skinner, 1996).

Transaction Cost Economics is generally used to explain the structure of organizations and why certain business transactions are chosen over others. TCE assumes that firms will act to minimize costs, including both out of pocket expenses and costs associated with risk. The three risks that TCE identifies are asset specificity, environment, and opportunism. Putting TCE into the context of the product architectural complexity, interconnections within the product architecture represent transactions, and related costs include direct production costs, as well as costs associated with the risks of asset specificity and the environment. Opportunism would not be applicable, as the components are not independent actors possessing the capacity to rationalize their actions. The implication of TCE in this context is that a rational actor (the design engineer) will seek to minimize the total number and concentration of transactions, the cost of components, and the influence of the environment.

Using TPF and TCE as theoretical frameworks, propositions can be constructed that, when tested, will advance the theoretical understanding of the impacts of product complexity on operations. One example for each dimension of complexity follows.

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sity. Practically all of these waves are driven by, enabled by, or amplified by the advances of electronic commerce over the past fifteen years. Successful competitors are those who find ways to surf at least one of these six kinds of waves without being inundated by the others. Moreover, they find ways to cope with environmental storms that arise, sometimes quite unexpectedly, so as not to be knocked off course, sink into an abyss of mediocrity, or worse. It is in this turbulent environment that decisions must be made. Collaboration in the making of these decisions potentially gives a wider base (of knowledge), a more expansive span (of attention), and a greater flexibility (of processing) for dealing with the turbulent environment in PAIR directions.

The SoC ideas portrayed in Figure 5 provide a frame of reference for future consideration and study of the CDM nexus linking EC and SC. By their very nature, EC+CDM+SC structures are necessarily concerned with knowledge, networks, and processes. In the interest of helping organizations survive and even excel in the competitive environment, the decision sciences community needs to more fully elucidate the design and implementation possibilities for EC+CDM+SC structures and their connections to competitiveness. Here we have endeavored to furnish some ideas and structure that may offer guidance in taking on this task.

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As the number of products offered or components required to manufacture a product increases, the effort dedicated to ensuring conformance will increase. The cost increases because 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). Further, these costs will grow at a decreasing rate due to better utilization of the quality function's infrastructure. Therefore, Proposition 1:

> P1: As multiplicity increases, the cost of inspection for conformance quality will increase at a decreasing rate.

Greater interconnectedness in the product architecture creates greater interdependence among functional subunits. This results in greater difficulty diagnosing, isolating, and repairing product failures (Karmarkar et al., 1987). Therefore, while the frequency of product failures may not be affected by the interconnectedness of product elements, the cost to re-work failed products will increase. Similarly, if an assembly is used across several products in the portfolio, its failure will have larger ramifications than had it been used in a single product. This leads to Proposition 2:

> P2: As interconnectedness increases, warranty costs will increase.

In conclusion, by formalizing the definition of complexity and clearly specifying the underlying dimensions, appropriate theoretical perspectives can be identified. These perspectives then become the guide by which the topic is explored, the ultimate result being further development of TPF and TCE, theoretical understanding of product complexity, and the opportunity to use the improved understanding to improve practice. ■

References available in the pdf version of the article on the October 2007 Decision Line Web site or upon request from the author.