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MODULARITY AND COMPLEXITY: AN EXAMINATION OF THE EFFECTS OF PRODUCT STRUCTURE ON THE INTRICACY OF PRODUCTION SYSTEMS

By

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ABSTRACT

MODULARITY AND COMPLEXITY: AN EXAMINATION OF THE EFFECTS OF PRODUCT STRUCTURE ON THE INTRICACY OF PRODUCTION SYSTEMS

By

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Applications of product modularity have increased sharply over the last decade, as more firms are adopting product modularity as their principal product design strategy due to its potential to increase the speed of product development in the face of dynamic competitive environments. Product modularity has also been advocated an effective means of managing complexity. While this may be the case for the structure of products themselves, the effects of implementing of a modular product design strategy on the organizational systems that support the manufacture of modular products are not as well known. This study represents an attempt at assessing this impact, as it investigates the effects of product modularity on the complexity of production systems.

This study applies a systems theoretic framework and Seemingly Unrelated Regression (SUR) to empirical analysis of the effects of product modularity on production system complexity. The results suggest the product modularity is positively associated with the complexity of internal manufacturing processes and supply networks in situations of high outsourcing and high environmental uncertainty. The study also provides empirically validated perceptual measures

of product modularity, manufacturing process complexity, organizational complexity, and supply base complexity.

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1.0.0 Introduction

Business environments in the 21st century are becoming increasingly challenging due to global competition, rapid advancements in technology, growing pressure to reduce product development cycle times, and the emergence of more sophisticated and demanding customers. The concept of modularity has been advanced as one effective strategy to offset some of the increasing complexity faced by businesses in this era of frequent and rapid change.

Modularity refers to the hierarchic structure of a system whereby it is composed of smaller subsystems that can be designed independently, yet function together as a whole (Baldwin and Clark, 1997). Modularity has been credited with enabling the innovation and commercialization surge experienced by the computer industry over the last three decades (Baldwin and Clark, 2000), and its rapid diffusion into other industries such as automotive, consumer electronics, home appliances, and even services has begun to receive the increased attention of top managers, analysts and researchers (Andrews, 2000; Worren, Moore and Cardona, 2002; Salz, 2006; Hagel and Brown, 2008). Although modularity is not a new concept (it is over 40 years old), the recent increase in its deployment raises new questions regarding the broader implications of its application. This study is focused on understanding the effects of product modularization beyond its influence on the product itself, to its impact on the organizational systems that support the manufacture of modular products.

Complexity refers to the presence of many, varied parts, patterns or elements, connected in a way that makes an object difficult to understand fully (Baldwin and Clark, 2000). Extant literature suggests that a relationship exists between modularity and complexity at the product level (Simon, 1962; Ulrich, 1995; Salvador et al., 2002) and also at the organizational level (Orton and Weick, 1990; Galunic and Eisenhardt, 2001; Schilling and Steensma, 2001), but few studies have examined the relationship between modularity and complexity *across* organizational levels. The research presented here begins to address this void by investigating the following research questions:

1) *Does employing modularity at the product level impact the level of complexity of supporting production systems?*
2) *What factors may impact how modularity affects production system complexity?*

A production system is herein defined as a firm's internal manufacturing process, its organizational structure, and its supply base.

Consistent with the heritage of rigorous academic research on modularity and complexity, a systems perspective has been adopted for this study. Systems Theory draws on the notion that both man-made and naturally-occurring systems have common characteristics (Boulding, 1956). This allows for the application of insights drawn from the study of natural systems to the examination of other organizational phenomena. In this study, elements of Systems Theory are applied to the understanding of product modularity's influence on production system complexity.

The research presented here makes a number of significant contributions to the Operations and Supply Chain Management body of knowledge and to business practice. First, to support the examination of the phenomena of interest, this research provides empirically validated perceptual measures of product modularity, manufacturing process complexity, organizational complexity, and supply base complexity. Perceptual measures of modularity and complexity have been called for in prior studies of these concepts (Choi and Krause, 2006; Salvador, 2007). Additionally, the results provide insight regarding the applicability of systems theoretic perspectives in predicting structural characteristics of manufacturing systems. Finally, the results provide insight to managers regarding the system consequences of the choice to modularize products.

This study is organized as follows: Chapter 2 provides a review of the literature pertinent to this investigation, followed by a discussion of the theoretical framework applied to this analysis, and the presentation of hypotheses in Chapter 3. Chapter 4 provides detail regarding the research design and data analysis is covered in Chapter 5 (Measurement Analysis) and Chapter 6

(Hypothesis Testing). The study concludes with a discussion of the contributions and limitations of this research, as well as recommendations for future study in Chapter 7.

2.0.0 Literature Review

The literature reviewed in this chapter covers three topics: 1) modularity research in Operations and Supply Chain Management; 2) the relationship between modularity and complexity; and 3) the composition of the modularity and complexity constructs.

2.1.0 Modularity Research in Operations and Supply Chain Management

While much of the literature on modularity and modular systems resides in the engineering domain, there is a small, but solid base of research on the topic that has a high degree of relevance to Operations and Supply Chain Management (OSM). This section segments these studies by method of analysis (i.e., conceptual, empirical, analytical and simulation), and discusses their contributions to the OSM body of knowledge.

2.1.1 Conceptual Foundation

Starr (1965) introduced the concept of Modular Production to the academy. His work suggested that the production process be broken up into two distinct process types: transformational processes and assembly processes. Transformational processes deal with the conversion of raw materials into product components, while assembly processes deal with the connection of product components to produce a finished product. He suggested that segmenting the process in this way allowed for greater emphasis to be be placed on producing components that could be combined into a variety of finished product configurations. This introduction to modular production represented a significant departure from the typical mass manufacturing logic that dominated the era.

The interest of the OSM research community in modularity was reignited nearly three decades later as studies by Langlois and Robertson (1992) and Ulrich (1995) suggested that product modularity could facilitate part standardization, which enables a potential reduction in the complexity of purchasing, inventory management, quality control and field service. Interest in the concept continued to gain momentum as Fine (1998) and Baldwin and Clark (2000) added more refined theoretical perspectives through their discussion of the interrelated nature of product structures and organizational task structures. They suggest that the concurrent design of products, manufacturing processes and supply networks is crucial in order to effectively produce and extract maximum value from modular products.

2.1.2 Empirical Analysis

Empirical studies on modularity in OSM have primarily focused on the effects of product modularity on firm performance. Worren et al. (2002) found an indirect relationship between product modularity and firm performance (mediated by model variety) in their study of the US and UK appliance industries, while Lin (2003) failed to detect a significant relationship between product modularity and firm performance in his analysis of computer and electronics manufacturers in

Taiwan. Significant relationships between product modularity and delivery, flexibility, and customer service were, however, detected by Antonio et al. (2007) in their analysis of manufacturers of electronics, toys, and plastics in Hong Kong. These mixed findings suggest that there is much more to be learned about the intermediary mechanisms that link modular product architecture to firm performance. Other empirical studies on modularity in OSM have sought to establish modularity's ability to facilitate a mass customization strategy (Duray et al., 2000; Tu et al., 2004), and found strong evidence to illustrate its performance in this application.

2.1.3 Analytical and Simulation Modeling

Analytical and simulation studies examining modularity within OSM contexts have been somewhat more scarce. Ernst and Kamrad (2000) develop an analytical model to illustrate the value of coupling product modularity and logistics postponement. The model is used as a basis for a static simulation of three cases which demonstrate the costs benefits of pursuing the two strategies simultaneously. Fine et al. (2005) use a goal programming approach to investigate whether complementarity exists between product structures and supply chain structures. Results suggest that modular product – modular supply chain combinations, as well as integral product – integral supply chain combinations outperform mixed structure combinations (i.e., modular product – integral supply chain, and integral product – modular supply chain combinations).

Although the studies reviewed here broadly establish that product modularity may have an impact on the structure and performance of production systems, explicit tests of modularity effects on structural and operational characteristics of manufacturing systems have yet to be performed.

2.2.0 The Relationship between Modularity and Complexity

Throughout the operations and organizational management literature on modularity, there exists the assumption that the modularity-based strategies reduce complexity (Ethiraj & Levinthal, 2004). Baldwin and Clark (2000), in their retrospective of the evolution of the computer industry, suggest that modularization reduces the structural complexity of products in the design phase by minimizing the number of interdependencies among product components. Langlois (2002) implies that lower levels of structural complexity in modular products results from the reduction in the number of components from which they are comprised. This rationalization of parts is credited to the consolidation of lower level components into pre-assembled subsystems. Pil and Cohen (2006), on the other hand, suggest that it is the *perceived* complexity of a product that is actually lowered through the use of modular design, in that its readily decomposable structure makes it easier to ascertain how the product's configuration supports and enables its functionality.

Product modularity is also posited to reduce managerial complexity. Sanchez (1995) and Sanchez and Mahoney (1996) explain that a great deal of the coordination required for product development is embedded in the structure of a modular product through the use of standardized interfaces. These interface standards set forth specific criteria required for the integrating of a component into the finished product, and therefore reduce the need for coordination between component designers during product development. Ulrich (1995) suggests that the elimination of these task interdependencies allows for a more systematic approach to the management of product development projects. He further suggests that the reuse of common components, enabled by employing a modular product structure, simplifies the supply-side tasks of purchasing and quality control. This sentiment is echoed from the demand side by Feitzinger and Lee (1997) who suggest that product modularity, coupled with a postponement strategy, simplifies product customization, inventory management and market mediation.

Perhaps the most pervasive view of modularity's effect on complexity considers the adaptable nature of modular products, and how this adaptability enables a rapid product response from firms competing in dynamic business environments. Langlois and Robertson (1992) and Garud and Kamuraswamy (1995) explain that in dynamic environments, the cognitive complexity facing managers increases under the constant pressure to innovate and adapt. They suggest that the modularization of products enables components to be more easily outsourced, thereby reducing the scope of internal development and production activities. The resultant external development capability allows for potentially faster and broader component innovation, through competition in the supply market (Fine, 2000), with marginal or no increase in internal operation complexity.

Management scholars laud the value of organizational modularity in coping with environmental complexity. In their study of 10 divisions of a Fortune 100 high-technology firm, Galunic and Eisenhardt (2001) show that organizational modularity facilitates the reorganization of firm resources to quickly respond to emerging opportunities, as well as to stave off competitive threats and shore up performance slippage in active operations. Also, Schilling and Steensma (2001) demonstrate in an empirical analysis of data on 330 manufacturing industries that modular forms of organization are a common response to high levels of heterogeneity and technological change in a variety of competitive and complex business environments.

More recently, however, researchers are beginning to challenge the assumption that modularity-based strategies reduce complexity. Salvador (2007) points out that complexity arises as a result of a system's ability to take on many configurations, and Staudenmayer et al. (2005) discovered in their case studies of seven firms from various industries that employing modularity in products increased the complexity of product development activities considerably. These observations suggest that some ambiguity may exist regarding modularity's effect on complexity. The purpose of this study is to provide further insight into the relationship between modularity and complexity by performing careful measurement of these constructs, and executing tests of the relationship between product modularity and production system complexity in various competitive contexts.

Table 2.1 below offers a summary of the literature reviewed here, as well as some other key modularity research themes in Operations and Supply Chain Management.

Table 2.1 Summary of product modularity literature relevant to Operations and Supply Chain Management

Key Themes	**References**
Modularity in products is a key enabler of mass customization	Starr (1965); Duray et al. (2000); Tu et al. (2004)
Product modularity has a positive effect on firm performance	Worren et al. (2002); Lin (2003); Antonio et al. (2007)
Product modularity accelerates innovation	Henderson and Clark (1990); Langlois and Robertson (2002); Sanchez and Mahoney (1996); Baldwin and Clark (1997, 2000); Fine (2000)
Product modularity facilitates the design and coordination of supply chains	Fine (2000); Fixson (2005); Ro et al. (2007)
Product modularity reduces product complexity	Baldwin and Clark (1997, 2000); Langlois (2002); Pil and Cohen (2006)
Product modularity reduces management complexity in new product development	Sanchez (1995); Ulrich (1995); Baldwin and Clark (2000)

Table 2.1 (cont.)

Product modularity may increase complexity in operations and supply management	Salvador et al. (2002); Staudenmeyer et al. (2005)

2.3.0 Composition of the Modularity and Complexity Constructs

2.3.1 Modularity

Modularity refers to the hierarchic structure of a system whereby it is composed of smaller subsystems that can be designed independently, yet function together as a whole (Baldwin and Clark, 1997). Each dimension of the modularity construct will be introduced and discussed in the following sections.

Functional Binding

Functional Binding refers to the compartmentalization of the designed functions of a system. If a system exhibits high functional binding, each designed function is confined to a minimal number of components, with one-to-one correspondence between designed functions and system components representing an ideal condition. Designed functions refer to those functions which are intentionally included in the system, and can be isolated, controlled and modified by the designers of the system.[1] The term functional binding is credited to Stevens, Myers and Constantine (1974), but was reintroduced to management literature by Salvador (2007).

[1] This classification excludes emergent functions (i.e., anomalies, glitches, etc.) which are unintended and occur as a result of unplanned interaction of designed functions.

Functional binding underlies modularity in that its presence suggests a system that is partitioned in a way that reduces the interdependence of components and allows for their independent design. Although different terms are used to describe the concept (e.g., architecture; function to component allocation; functional mapping; module partitioning), the underlying meaning remains consistent, and it is acknowledged as a critical dimension of modularity by a number of seminal works in the area (Henderson & Clark, 1990; Ulrich, 1995; Baldwin & Clark, 1997; Fixson, 2005).

Several attempts to measure modularity using perceptual scales have included items that tap the functional binding dimension. Duray et al. (2000) do so by inquiring about the interchangeability of product features and options, while Worren et al. (2002) and Antonio et al. (2007) ask questions regarding the ability of designers to make changes in key product components without changing others. Also, Duray et al. (2000) and Tu et al. (2004) assess functional binding by including items addressing the ability to directly add features and options through the addition of a module.

Interface Standardization

Interface standardization is the presence of common, previously agreed upon conduits for interaction between the complementary components of a system. Some characteristics that are typical of standardized interfaces are: 1) they tend to remain unchanged over extended periods of time; 2) their specifications are widely known among stakeholders of the system components to be connected; and 3) they enable the open interchange of complementary system components. Interface standardization has also been widely recognized by scholars as undergirding the modularity construct (Garud & Kumaraswamy, 1995; Ulrich, 1995; Sanchez & Mahoney, 1996; Baldwin & Clark, 1997).

Of the studies that used perceptual measures of modularity, only two have included items that tap the interface standardization dimension. Lin (2003) simply asks respondents to indicate the degree to which their product's interfaces are standardized, whilst Worren et al. (2002) attempt to assess the level of interface standardization present in organizations by inquiring about the extent to which business processes are standardized across departments.

Decomposability

Decomposability describes the ease with which a system can be separated into its constituent parts. It also implies that the system can be readily reconstructed from the same, similar, or supplementary components without necessarily suffering significant performance deterioration. Decomposability is the aspect of modularity most responsible for its flexibility, as it makes component swapping (a key benefit of modularity) practical.

Of the three dimensions of modularity, decomposability is the one most frequently represented in its perceptual measurement. Items tapping this dimension ask directly about the separability of products (Worren et al., 2002; Antonio et al., 2007) or the ability to recombine or reassemble products (Lin, 2003; Tu et al., 2004). Tu et al. (2004) also address the decomposability of manufacturing processes by posing questions about their adjustability.

2.3.2 Complexity

Complexity is the presence of many, varied parts, patterns or elements, connected in a way that makes an object difficult to understand fully (Baldwin and Clark, 2000). In the sections below, each of the proposed complexity dimensions are defined and discussed.

Number of Components

There is wide consensus among scholars of many disciplines that the number of components of a system contributes to its complexity (Simon, 1962; Kauffman, 1995; Choi & Krause, 2006). The inclusion of this dimension in the complexity construct can be grounded via the concept of bounded rationality – the notion that there are constraints to the information processing capabilities of decision makers, and that their behavior in response to receiving additional information is markedly less rational (Simon, 1957). As the number of components of a system increases, the amount of information on hand also increases, approaching or surpassing the information processing limits of the decision maker. This inhibits the decision maker's ability to accurately perceive the system, thereby making it appear more complex.

Many studies in Operations Management (OM) that have employed perceptual measures of complexity have captured the number of components dimension. At the product level, Sawhney and Piper (2002) asked respondents to report the number of layers in printed circuit boards as one component of a three-item complexity measure, and Devaraj, Hollingworth and Schroeder (2004) capture the number of product lines in respondents' manufacturing plants as part of their complexity measure. At the market and supply chain levels, Flynn and Flynn (1999) include the number of customers served in their measure of manufacturing environment complexity and Vachon and Klassen (2002) used an estimate of supply network size as a component of their measure of supply chain complexity.

Heterogeneity

Heterogeneity refers to the presence of characteristic differences in the units that make up a system. For physical systems, this could refer to differences in the geometry, materials of construction, or functions of units; and for non-physical systems, heterogeneity could refer to differences in objectives, procedures or protocols of system components. Like the number of components, heterogeneity is also broadly accepted as a dimension of complexity (Thompson, 1967; Child, 1972; Holland, 1995) and can be conceptually linked through the concept of bounded rationality. As diversity in system components increases, the types of information to be processed by the decision maker also increase. This expanded scope of information present in the system may exceed the processing capabilities of the decision maker, making the system more difficult to perceive accurately and therefore more complex.

The representation of heterogeneity in perceptual measures of complexity in Operations Management (OM) studies has been relatively low, appearing in only two identified studies. Flynn and Flynn (1999) used averages of multi-item scales measuring labor diversity, output diversity, manufacturing diversity and process diversity in their manufacturing environment complexity construct and Vachon and Klassen (2002) used a measure of product variety to capture heterogeneity in their supply chain complexity construct.

Interdependence

Interdependence refers to the level of connectedness among the components of a system, as indicated by the number of linkages among components and/or the number of interactions that occur among components. The interdependence dimension is central to the complexity construct because it is the element that most reflects a system's potential to exhibit unwieldy behavior. In highly interdependent systems, a change to one part of the system tends to propagate throughout the system. This propagation is capable of producing unanticipated effects (i.e., glitches) and non-linear response, both of which can obscure cause and effect relationships (Stacey, 1995). The resultant causal ambiguity is a key component of system complexity. This phenomenon has been borne out in a number of physical experiments and simulations that illustrate the magnitude of increased interdependence on system complexity (Holland, 1995; Kauffman, 1995).

Interdependence is the least represented of all dimensions of complexity as it pertains to perceptual measurement in OM applications. The literature search produced one study that related interdependence to complexity, albeit indirectly. Lewis (2004) included both complexity and interdependence in a construct labeled "task demands," a comparative measure of the additional effort required to complete one task relative to another. Furthermore, none of the studies discussed above used all three proposed complexity dimensions in their measurement. Most scales used one dimension (i.e., number, heterogeneity, or interdependence) in conjunction with items that measure the level of difficulty associated with an activity or items that directly ask about the complexity of an object.

Table 2.2 below offers a summary of the proposed dimensions of modularity and complexity, and references literature that supports the association of each dimension with its respective construct.

Table 2.2: Dimensions of Key Constructs

Dimensions of Modularity	**Supporting Literature**	**Dimensions of Complexity**	**Supporting Literature**
Functional Binding	•Salvador (2007) •Fixson (2005) •Ulrich (1995)	Number of Elements	•Choi & Krause (2006) •Novak & Eppinger (2004) •Flynn & Flynn (1999) •Thompson (1967)
Interface Standardization	•Salvador (2007) •Baldwin & Clark (1997) •Sanchez & Mahoney (1996) •Garud & Kumaraswamy (1995)	Heterogeneity	•Choi/Krause (2006) •Novak/Eppinger (2004) •Flynn/Flynn (1999) •Thompson (1967)
Decomposability	•Salvador (2007) •Schilling (2000)	Interdependence	•Choi/Krause (2006) •Novak/Eppinger (2004) •Simon (1967)

2.4.0 Chapter Summary

In this chapter, a review of the literature on modularity research in Operations and Supply Chain Management was performed, as well as an analysis of the literature concerning the relationship between modularity and complexity. Finally, the dimensions of the modularity and complexity were researched, and a discussion of prior attempts at perceptual measurement of the modularity and complexity constructs was offered. The next chapter introduces the study's theoretical framework and presents the hypotheses to be tested.

3.0.0 Theory, Research Models and Hypotheses

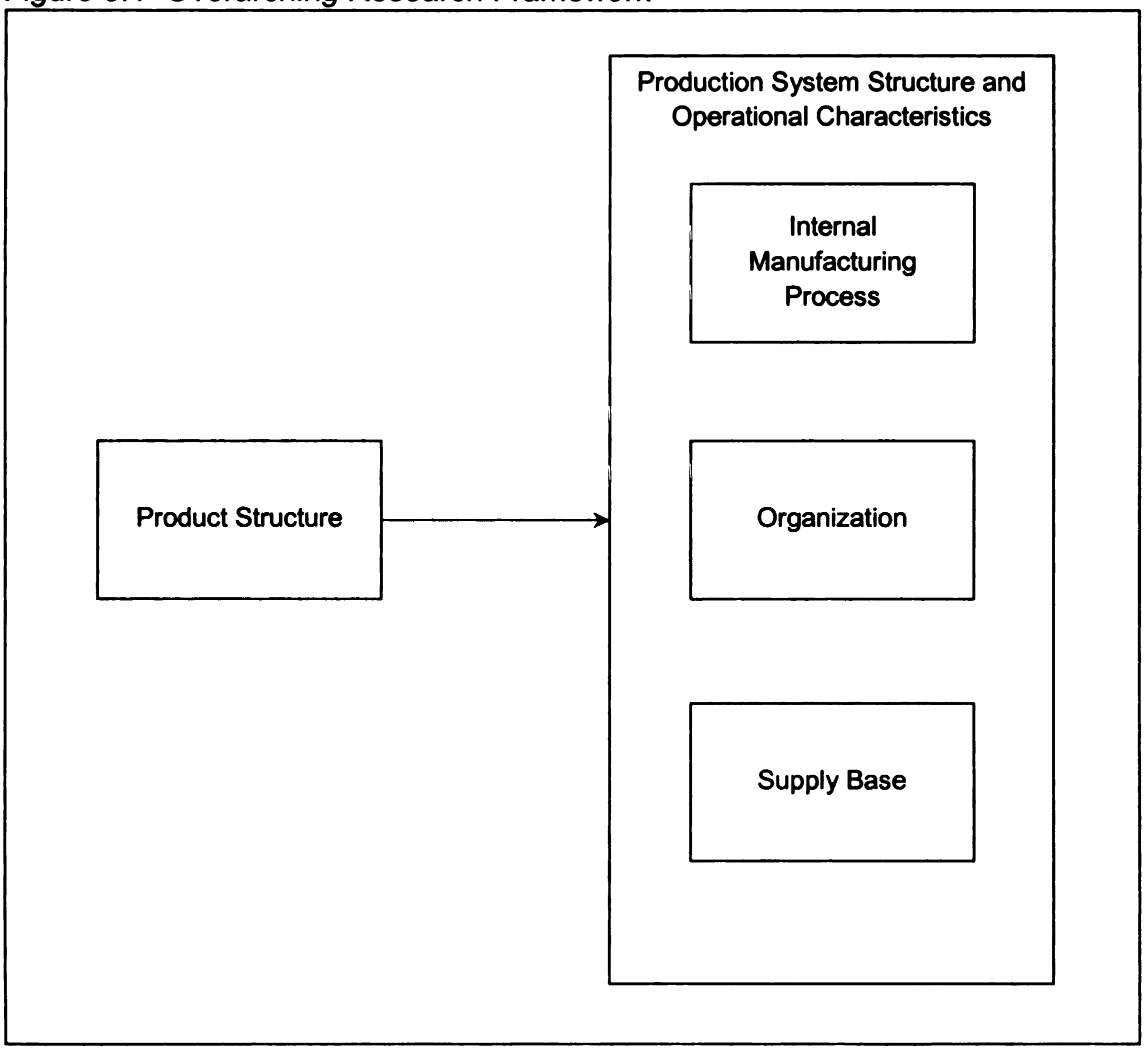
This chapter provides the theoretical basis for the investigation, introduces each of three research models to be analyzed, and presents a set of twelve hypotheses to be tested.

3.1.0 Theoretical Basis

To guide the examination of the effects of product modularity on production system complexity, a systems theoretic perspective has been adopted. Systems Theory is relevant for analysis of this phenomenon for a number of reasons. First, it provides a grounded framework for the examination of multi-level phenomena – situations where the effect of a change or stimulus within a particular locale has implications beyond its defined bounds (Short, Ketchen Jr., Palmer, & Hult, 2000). This comes to bear in the current study, as it examines the effect of structural choices at the product level on the structural characteristics of the supporting production system. Second, by virtue of its interdisciplinary nature, Systems Theory allows for importation of concepts and explanatory mechanisms describing system behavior from a vast repository of scientific learning (Boulding, 1956). In the present study, characteristics of open and closed systems are applied to the study of complexity in manufacturing systems. Third, Systems Theory has a history of use in aiding the understanding of organizational behavior (Thompson, 1967), and recent studies of modularity and complexity have adopted the systems perspective. Schilling (2000) used General Systems Theory as a framework to develop a model to explain the motivations for interfirm product modularity, and Baldwin and Clark's (2000) study of the transformation of the computer industry (ignited by the use of modular product architecture) has Complex Adaptive Systems as its theoretical foundation.

The basic proposition advanced by Systems Theory, as it is operationalized for this study, is summarized in Figure 3.1 below:

Figure 3.1 Overarching Research Framework



3.2.0 Research Models

This investigation is divided into three separate research models: an exploratory model, a contingency model, and a moderation model. The exploratory model seeks to answer the question of whether or not product modularity is associated with complexity in production systems, while the contingency model is directed toward understanding what factors determine whether product modularity is associated with either increased or decreased production system complexity. Finally, the moderation model examines whether or not the strength of the proposed relationship between product modularity and production system complexity is affected by the level of uncertainty in the manufacturing environment.

3.2.1 Exploratory Model

When modularity is employed at the product level, there are likely to be consequences for a firm's internal manufacturing processes. Some researchers suggest that manufacturing processes used in the creation of modular products are simpler. Schilling (2000) argues that product modularity facilitates the decoupling of manufacturing processes, allowing processing steps to be performed independently on separate subsystems – a simpler approach in comparison to the highly coordinated processing requirements for integrated products. Salvador et al. (2002) suggest that it is the reduction in the number of required operations owed to the receipt of completed sub-assemblies that simplifies the manufacturing process, while Fixson (2005) argues that the use of plug-and-play type component interfaces reduces the need for a variety of approaches to integrating components into finished products. Other scholars suggest that production of modular products could make manufacturing processes more complex. Baldwin and Clark (1997) note that product modularity can destabilize the manufacturing process, as frequent modifications are likely required to produce the larger range of product variants enabled by employing a modular product architecture, and Nyaga et al. (2007) indicate that the configure-to-order (CTO) manufacturing processes associated with modular products often require increased manufacturing capacity to effectively address the demand for a broader range of product variants.

While the literature offers somewhat conflicting perspectives on the relationship, it strongly suggests that product modularity influences the structural and operational characteristics of manufacturing processes. As such, the first hypothesis proposes that product modularity impacts the complexity of manufacturing processes.

H1: Product modularity influences the complexity of internal manufacturing processes.

Adopting a modular product architecture may also have an impact on the way an organization is structured. Henderson and Clark (1990) suggest that the structure of product creating organizations tends to mirror the structure of their products. If organizations do indeed reflect the structures of their products, then within the context of product modularity, organizations would be expected to exhibit a more decentralized structure, with authority to set objectives and policy distributed among the divisions of a firm. In this situation, it could be argued that the organization itself would be more complex, due to the presence of many different policies and business processes across the organization. Alternatively, Baldwin and Clark (2000) noted IBM's need to add a powerful central authority during the design and production of their first modular computer system in order to monitor progress and ensure compliance with established system standards. Langlois (2002) also highlights the critical need for centralized coordination when employing modularity in products to ensure that modules are integrated in manner which extracts maximum value from system production. In this case, the presence of common policies and standard practices that are consistent with centralized organizations would suggest simpler, more uniform organizations.

Although there is not unequivocal support in the literature for either perspective on product modularity's effect on organizational designs, it suggests that modularity dictates some organizational response in order to effectively manage the production and commercialization of products. Hypothesis two examines whether or not product modularity affects the complexity of manufacturing organizations.

H2: Product modularity influences the complexity of organizational design and coordination.

A firm's supply base is also likely to be affected by the adoption of a modular product architecture. Modularity allows for the incorporation of a variety of complementary product components through the use of standardized interfaces, and while theoretically their use should reduce the number of interdependencies among firms collaborating to produce modular products (Sanchez and Mahoney, 1996), empirical findings suggest the contrary. The following was observed in recent case studies of firms employing modular product architectures: "While an environment of interfirm (product) modularity should in theory eliminate interdependencies among firms…interdependencies continually emerged throughout the product development process, despite attempts to limit them…the quantity and variegated nature of external relationships made their management exceedingly difficult…The sheer complexity was daunting, given both the size of the external network as well as the number of ties per external collaborator." (Staudenmayer, Tripsas, & Tucci, 2005, p. 303) This finding suggests that product modularity increases supply base complexity.

Alternatively, product modularity may also reduce the complexity of a firm's supply base. Consider the situation where a firm initially produces a product component internally. All the individual parts that make up that component must be procured, and in many cases separately. Now consider the situation where a firm procures the same component as a modular sub-assembly from a first-tier supplier. In this situation, the focal firm has reduced the size of their supply base by as much as n-1 (where n equals number of components in the sub-assembly)[2], and effectively shifted the coordination effort of parts procurement and perhaps even component development to their supplier. Case studies performed by Salvador et al. (2002) provide examples of this scenario from the home appliance and heavy truck industries.

Again, the literature does not provide unequivocal insight regarding product modularity's influence on the supply base, however, it does suggest that the supply base is affected by the deployment of modularity at the product level. Accordingly, hypothesis three (H3) proposes a relationship between product modularity and supply base complexity.

H3: Product modularity influences the complexity of a firm's supply base.

Hypotheses one (H1) through three (H3) are summarized in Figure 3.2 below.

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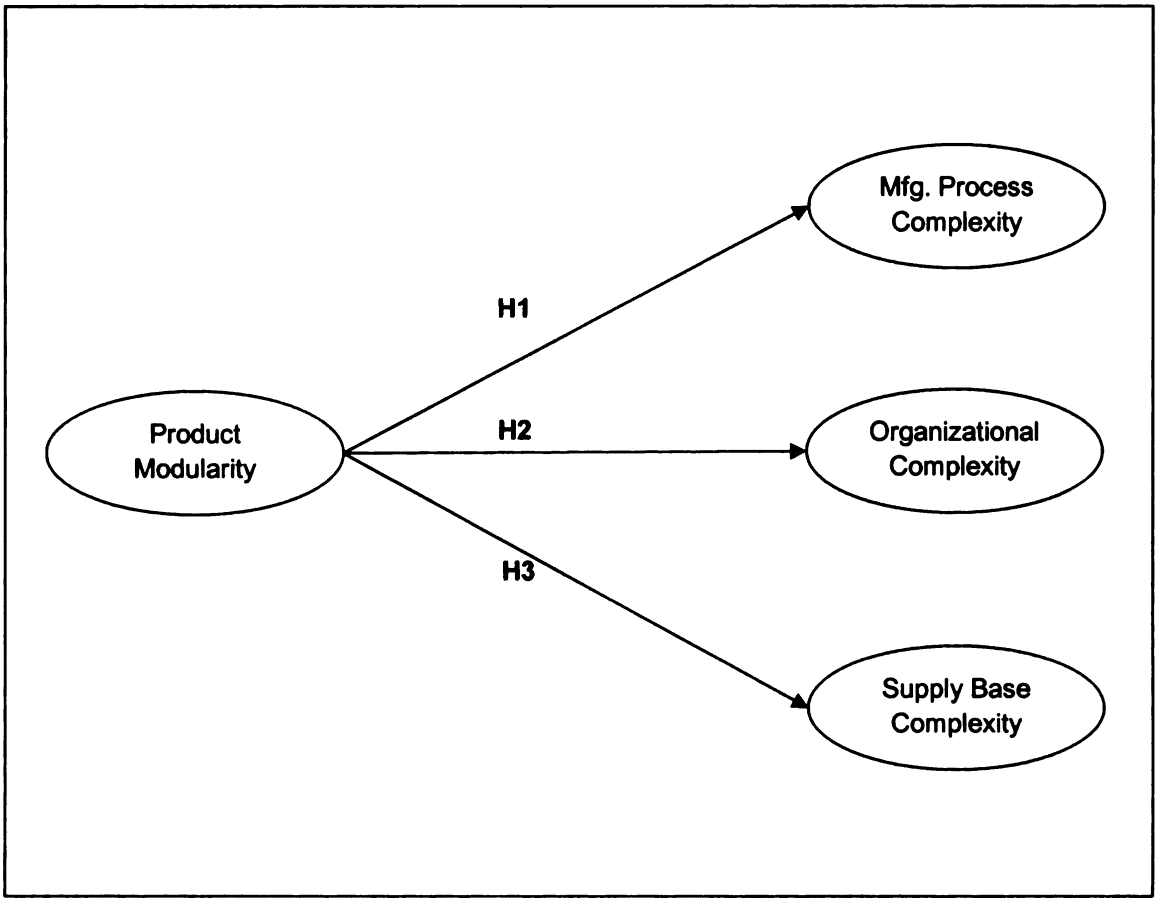
[2] Assumes single sourcing

Figure 3.2: Exploratory Model



3.2.2 Contingency Model – Open versus Closed Systems

An aspect of Systems Theory that is relevant to the study of complexity is the concept of entropy. Entropy is a measure of disorder in a system, and it increases as the number of configurations that a system can occupy increases (Kauffman, 1995). The number of configurations a system can occupy is proportional to the number of system elements, the diversity of elements present in the system (i.e., its heterogeneity), and the number of connections that are possible among the elements of a system (i.e., its level of interdependence). From the discussion of the dimensions of complexity in Chapter 2, it can be observed that entropy and complexity are closely related concepts. In fact, prior studies have even used measures of entropy as indicators of manufacturing system complexity (Deshmukh, Talavage, & Barash, 1998). This study proposes that entropic behavior in physical systems can provide critical insights regarding complexity behavior in production systems.

Katz and Kahn (1978) distinguish between two types of systems based primarily on their entropic behavior, closed systems and open systems. Closed systems are purported to respond to changes introduced into the system by *increasing* in entropy, while open systems respond by either maintaining their current level or *decreasing* in entropy. For organizations, "closure" and "openness" can refer to their span of control (Thompson, 1967), or in an extended enterprise context, their span of influence. When viewed in this way, closure resulting in increased entropy (complexity) and openness leading to decrease in the level of entropy (complexity) can be reconciled. As a case in point, when manufacturing organizations grow, the scope of operations that sustain them necessarily grows – new products are introduced into the portfolio; new technologies are added to manufacturing processes; new markets emerge that require different marketing strategies, legal compliance requirements, and so on. To the extent that organizations strive to maintain these emergent activities firmly under their span of control or influence, operations become more complex. This occurs because organizations are boundedly rational (Williamson, 1975). On the other hand, if organizations relinquish their authority over certain aspects of operation, complexity may be limited.

Viewing production systems associated with modular product architectures as open and closed systems may provide insight into why conflicting views exist in the literature regarding modularity's influence. In the case of a closed system, a firm employing product modularity may act as both a "module producer" and a "system integrator," retaining responsibility for design and production of system components, as well as system architecture design, system integration, and system configuration. Based on the argument presented above, a firm in this situation is likely to experience higher levels of complexity. Alternatively, a firm resembling an open system would function primarily as "system integrator," leaving the design and production of system modules to external suppliers. This decrease in the scope of operations would likely result in reduced complexity. Hypotheses four through six represent this contingency view of product modularity's influence on production system complexity.

H4a: In closed systems, product modularity is positively associated with the complexity of internal manufacturing processes.

H5a: In closed systems, product modularity is positively associated with the complexity of organizational design and coordination.

H6a: In closed systems, product modularity is positively associated with the complexity of firms' supply bases.

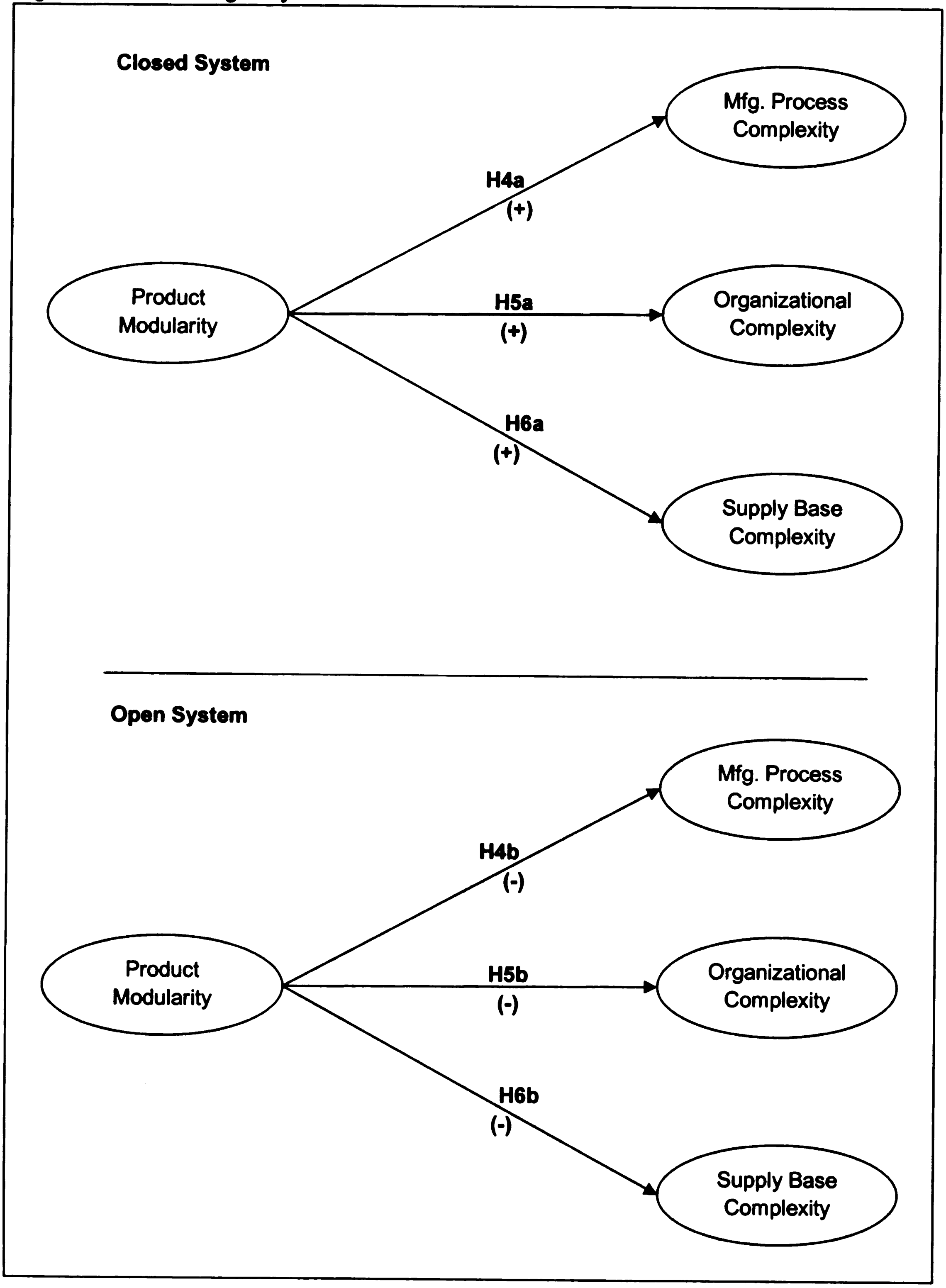
H4b: In open systems, product modularity is negatively associated with the complexity of internal manufacturing processes.

H5b: In open systems, product modularity is negatively associated with the complexity of organizational design and coordination.

H6b: In open systems, product modularity is negatively associated with the complexity of firms' supply bases.

Hypotheses 4a through 6b are summarized in Figure 3.3 below.

Figure 3.3: Contingency Model



3.3.3 Moderation Model – Effects of Environmental Uncertainty

Product Modularity is often cited as an effective strategy for offsetting the effects of environmental uncertainty (Langlois and Robertson, 1992; Garud and Kamuraswamy, 1995). The loosely coupled structure of a modular product architecture allows a product to be partitioned in such a way that changes to a segment of a product (i.e., a module) can be executed without significantly altering the design or operational characteristics of the product's other modules. These module-level changes, in most cases, can be made much more rapidly than the changes required to modify a product with an integral structure (Baldwin and Clark, 2000). This piecewise innovation capability enables firms to quickly respond to customer demand for new product features and incorporate new technologies.

Since this rapid response is likely to produce the greatest benefit in situations of high uncertainty, it is proposed that applications of product modularity will be higher in these situations, therefore causing its effect on production system characteristics to be more pronounced relative to its effect in low uncertainty environments.

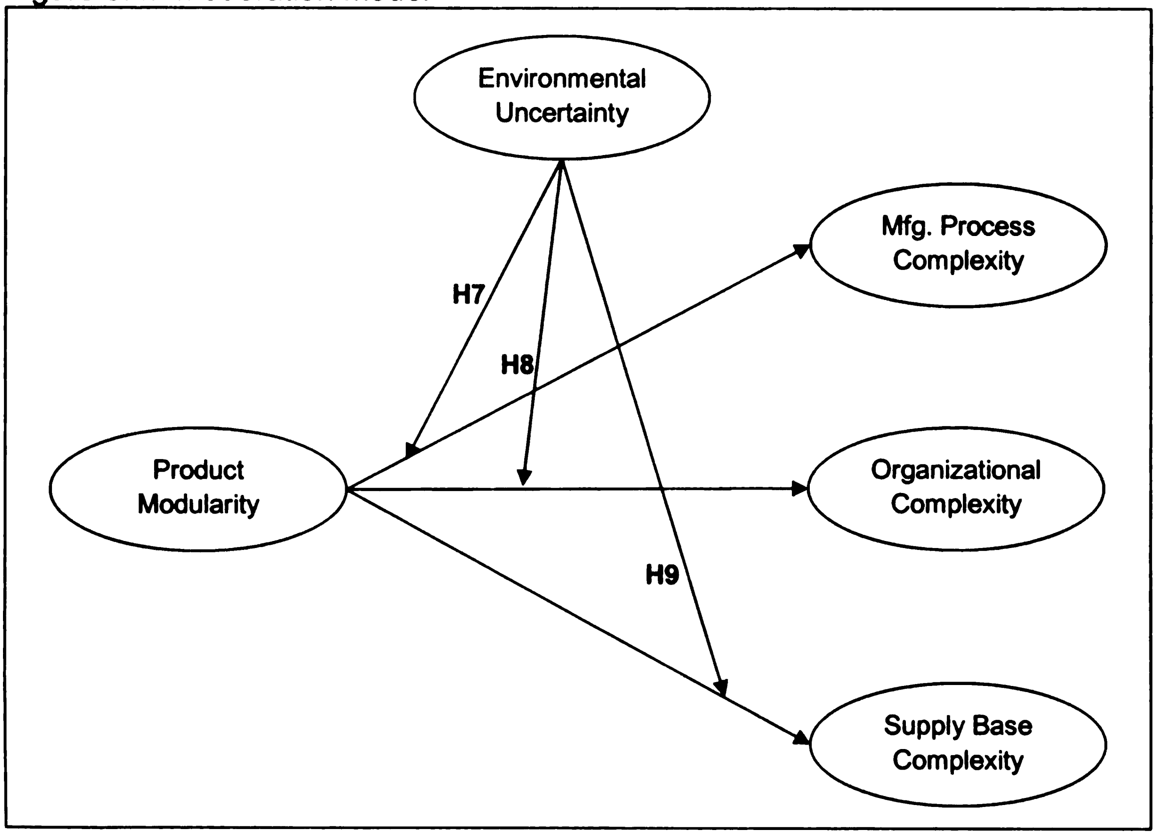
> *H7: The effect of product modularity on internal manufacturing process complexity is stronger under conditions of high environmental uncertainty, as compared to low environmental uncertainty.*

H8: The effect of product modularity on organizational complexity is stronger under conditions of high environmental uncertainty, as compared to low environmental uncertainty.

H9: The effect of product modularity on supply base complexity is stronger under conditions of high environmental uncertainty, as compared to low environmental uncertainty.

Hypotheses seven (H7) through nine (H9) are summarized in Figure 3.4.

Figure 3.4: Moderation Model



3.4.0 Chapter Summary

This chapter introduced and applied Systems Theory to the analysis of Product Modularity's relationship with Production System Complexity. Three research models were presented: an exploratory model, a contingency model, and a moderation model. For each model, hypotheses were developed based on deductive reasoning, literature support, and predictions from theory. The next chapter discusses the research design and implementation.

4.0.0 Research Design

In order to address the research questions presented in Chapter 1, an empirical study employing perceptual measures of the study's key variables was chosen as the most appropriate approach for the following reasons: First, the study's intent to span a large cross-section of manufacturing industries requires the use of a set of generic measures that are applicable across all contexts. Perceptual measures are well suited for this application because they can be designed specifically to extract the required information, while controlling for context-specific detail. Second, the study is concerned with capturing the outcomes of inter-related decisions of individuals at multiple levels of organizations. The number of decisions involved, their interaction, as well as the random component present in decision-making makes empirical analysis relatively efficient, as compared to purely analytical methods. Third, the intent of the study is to test and extend theory, which requires an assessment of the proposed relationships as they exist in actual production environments.

This chapter details the methods employed to collect the data required to address the study's primary research questions. Many of the procedures employed here were adapted from the recommendations of Dillman, Smyth and Christian (2009).

4.1.0 Questionnaire Design and Pretesting

The items appearing on the questionnaire were compiled using a search, select, modify and generate procedure. The search stage of the procedure involved a broad-based search of the terms *modularity*, *modular production*, and *complexity* on the academic search engines ProQuest and Google Scholar. The search was narrowed to empirical studies by including the term *empirical* as well as several terms associated with statistical analysis methods (i.e., Regression, Structural Equation Modeling, Factor Analysis, etc.) into the search criteria. Studies generated by the search were then evaluated for their relevance to Operations and Supply Chain Management applications by assessing source publication titles and article content. Cross-referencing of the selected studies was conducted via bibliographical analysis and the cited reference search feature on ISI's Web of Knowledge. This was performed in order to ensure inclusion of source studies from which the original items were generated, and subsequent works where measurement items were reused or refined. Recently published literature reviews (Fixson, 2007; Salvador, 2007; Roth et al., 2008) were also consulted as a final check against potential omissions. The final set included fourteen studies – five containing perceptual modularity scales, and nine with perceptual complexity scales. Table 4.1 below lists the sources for candidate measurement items evaluated for inclusion in the study.

Table 4.1: Perceptual Scales of Modularity and Complexity in OSM Research

Scale Name	**Source Study**
Modularity through fabrication	Duray et al. (2000)
Modularity through standardization	Duray et al. (2000)
Modular products	Worren et al. (2002)
Modular structure	Worren et al. (2002)

Table 4.1 (cont.)

Modular processes	Worrent et al. (2002)
Product modularity	Lin (2003)
Product modularity	Tu et al. (2004)
Process modularity	Tu et al. (2004)
Product modularity	Antonio et al. (2007)
Process structure complexity	Gupta and Lonial (1998)
Product line complexity	Gupta and Lonial (1998)
Manufacturing environment complexity	Flynn and Flynn (1999)
Process/product complicatedness	Vachon and Klassen (2002)
Management system complicatedness	Vachon and Klassen (2002)
Product complexity	Sawhney and Piper (2002)
Project complexity	Sarin and McDermott (2003)
Process structure complexity	Deveraj et al. (2004)
Product line complexity	Deveraj et al. (2004)
Complexity	Lewis (2004)
Project complexity risk	Wallace et al. (2004)
Information complexity	Prasad et al. (2005)

Each item appearing in the identified perceptual scales of modularity and complexity was then evaluated for potential inclusion in the study. An item was selected if: (1) it exhibited a high degree of fit with the phenomenon under study; and (2) it demonstrated consistency with the theoretically derived dimensions of modularity and complexity. Items failing to meet both criteria were dropped. Items meeting both of these conditions were retained. Those meeting either of the two conditions were modified. New items were generated for cases where existing items did not provide sufficient coverage of a construct's theoretical domain or cases where items were not relevant to the types of modularity and complexity under study.

Items measuring Environmental Uncertainty were adapted from Calantone et al. (2002). These items represent an abbreviated version of the widely adopted Miller and Droge (1986) Environmental Uncertainty scale. A single objective item measuring the percentage of components of a firm or SBU's primary products that are outsourced was included to serve as a proxy for system openness. Also, objective items capturing: 1) the number of internal manufacturing processes; 2) the number of divisions; 3) the number of organizational levels; 4) the number of worldwide locations; and 5) the number of suppliers utilized, were designed for use in this study.

An initial version of the questionnaire was pretested by a panel of four manufacturing professionals and three professors of Operations and Supply Chain Management. Refinement of the questionnaire was performed on the basis of recommendations this advisory panel. A copy of the questionnaire is available in Appendix A.

4.2.0 Target Population and Sampling Frame

The primary target for study was U.S. based producers of technically complex products. "Technically complex" refers to those products which are composed of a high number of components that interact in a non-simple way (Simon, 1962), and have a high proportion of moving parts (Novak and Eppinger, 2001). This group was targeted because modularity is primarily advocated as a means to manage the complexity of products, hence the presence of modularity in this population is likely. However, to ensure that sufficient variability was present in the sample for employing variance partitioning data analysis techniques, a secondary population – manufacturers of products which cannot be classified as technically complex, was included. The unit of analysis is a manufacturing unit, which in some cases was represented by an entire firm, and in others by a Strategic Business Unit (SBU).

The sampling frame for the study was generated by compiling contact information for prospective participants in three broad categories:

Category 1 – Producers of technically complex products and select Tier-1 suppliers

Category 2 – Individuals affiliated with Michigan State University who are employed by firms that produce technically complex products

Category 3 – Contacts drawn from databases of professional societies.

For category one, six focal firms were targeted for participation: 1) a commercial aircraft manufacturer; 2) an aircraft engine manufacturer; 3) a household appliance manufacturer; 4) an automobile manufacturer; 5) a manufacturer of heavy commercial, construction and agricultural equipment; and 6) a manufacturer of diverse commercial, construction and industrial equipment. Firms 2, 3 and 5 above agreed to participate in the study, and provided contact information for select Tier-1 suppliers. This effort resulted in a total of 516 contacts.

Contacts in category two were complied by analyzing databases of affiliates of the Department of Marketing and Supply Chain Management at Michigan State University. For each entry, a subjective judgment was made regarding contact inclusion based on characteristics of their firm's primary products, as identified by information available via firms' websites. This effort resulted in a total of 274 contacts.

For category three, electronic mailing lists were rented from two professional societies, the Society of Manufacturing Engineers (SME), and the Institute of Industrial Engineers (IIE). The selection criteria applied for the creation of each list were as follows: (1) NAICS industry classifications – 334 (Computer and Electronic Product Manufacturing) and 336 (Transportation Equipment Manufacturing); (2) Job function – Corporate Executive, Manufacturing Management, Manufacturing Engineering, Product Design and Development; (3) Location – United States. This effort produced a total of 1,426 contacts.

In total, 2,216 contacts were compiled. While many of the contacts obtained were producers/assemblers of technically complex products, many of the Tier-1 suppliers from category 1 were not. As mentioned above, these firms were included in the sampling frame for the purpose of assuring a sufficient level of variance in the data for the application of analysis techniques that involve partitioning of sample variance.

4.3.0 Survey Administration

The survey was administered in two parts with the intent of collecting data at two organizational levels. Part one addressed technical aspects of the enterprise – product and process characteristics, while part two covered managerial and administrative aspects of the enterprise – organizational and supply chain characteristics. Invitations sent to prospective participants asked individuals to complete the section that was most relevant to their current job function, and to supply a referral for an individual within their organization who was qualified to answer the remaining section. However, it was suggested that if the responding individual was qualified to answer both sections, to proceed in that manner.

The survey was administered online. The questionnaire was translated into HTML format via templates available through the survey hosting website. Invitees were required to enter a password in order to enter the survey. Questions were randomized within categories in order to reduce the potential for common method bias. Responses were saved upon completion of the final question, or at the end of a specified timeframe (48 hours) for which respondents could exit and then re-enter the survey at the same question.

For category one and two contacts (n=790), e-mail invitations sent directly to prospective participants were the primary mode of contact; however for a portion of the sample (n=269) invitation letters were sent via U.S. mail, and for a smaller portion (n=39) invitations were sent via e-mail to Tier-1 suppliers directly from a focal firm participant. Category one supplier contacts received invitation letters which contained logos and authorized signatures of the firm that provided the contact information. In all cases, individuals were directed to the survey website to complete the questionnaire. A total of two reminder notices were sent to invitees based on whether or not a response had been recorded between mailings. Mailings were spaced at a maximum of five business days apart, and a minimum of three days apart. All reminder notices were sent via e-mail. Samples of invitation and reminder notices are available in Appendix B.

For category three, contact information for invitees was not disclosed. All communication to invitees was conducted through a third party service provider hired by the professional society supplying the list. All invitations and reminders for this group were sent via email. As was the case for category one and two contacts, a total of two reminder notices were sent, with a minimum of three days and a maximum of five days between mailings. However, in this case invitees received reminder notices whether or not their response was recorded. This action was caused by the inability to identify individuals who had already responded due to non-disclosure of contact information for recipients by SME and IIE.

4.4.0 Response Statistics and Sample Characteristics

A total of 96 invitations were returned as undeliverable, bringing the total number of individuals initially contacted to 2,120. The number of individuals submitting usable responses totaled 281 for an effective response rate of 13.3 percent (281 / 2,120). In addition, 30 referrals were received, nine whom consented to participate and produced usable responses, bringing the total response rate up to 13.5% (290 / 2,150). See Table 4.2 below for a summary of response by contact category.

Table 4.2: Response by Category

	Category 1	Category 2	Category 3	Total
No. Contacted	482	227	1441	2150
No. of Responses	112	16	162	290
%	23.2%	7.0%	11.2%	13.5%

4.5.0 Test for Non-Response Bias

An assessment of non-response bias was made using a similar method to that which is recommended by Armstrong and Overton (1977). However, instead of using late respondents as a proxy group for non-respondents, this study uses individuals who provided partial responses (i.e., those who provided responses to less than 10% of the questionnaire items) to approximate the characteristics of non-respondents. In 51 partial response cases, individuals provided information regarding the number of employees in their firm or business unit, and in 36 cases partial responses contained information regarding total annual sales. T-tests were performed on mean values of these demographic items for partial responses versus complete responses (i.e, observations that contained responses to more than 90% of the questionnaire items). No evidence of a significant difference between the mean number of employees for complete versus partial response groups was found at a 10% significance level (p=0.313), nor was a significant difference in mean annual sales detected between the two groups (p=0.108). This result suggests that non-response bias may not pose a problem for making inferences about the population based on the findings produced from analysis of the sample collected for this study.

4.6.0 Sample Characteristics

As discussed in Section 4.3.0, the survey was administered in two parts. As a result, two separate samples were obtained, a sample containing responses to items of a technical nature (n=169) and a sample containing responses to managerial and administrative items (n=188). In addition, a third sample containing responses for organizations that provided responses to both managerial and technical sections was constructed from the data collected (n=94). Sixty-seven responses (67) in this paired sample resulted from individuals who answered both the technical and managerial sections of the survey, accounting for the difference between total reported responses received (n=290) and the combined responses to the managerial and technical sections of the questionnaire (n= 357). Further detail regarding the pairing of responses is provided in Section 6.1.0. Table 4.3 provides a summary of the key characteristics of each sample.

Table 4.3: Sample Characteristics

Managerial Sample (n=188)	**Number of Employees:**	Median=365
	Annual Sales:	Median=$61 Million (US)
	Industry:	
		Frequency (Percentage)
	Fabricated Metal Product Manufacturing	31 (16.5%)
	Electrical Equip., Appliance and Component Mfg.	24 (12.8%)
	Aerospace	23 (12.2%)
	Transportation Equipment Manufacturing	23 (12.2%)
	Primary Metal Manufacturing	15 (8.0%)
	Machinery Manufacturing	14 (7.4%)
	Miscellaneous Manufacturing	14 (7.4%)
	Computer and Electronic Product Manufacturing	9 (4.8%)
	Plastic and Rubber Products Manufacturing	7 (3.7%)
	Other	28 (14.9%)
	Respondent Title:	
		Frequency (Percentage)
	President / CEO	17 (9.0%)
	Vice President / COO	20 (10.6%)
	Director	22 (11.7%)
	Supply Chain Lead (or equivalent)	17 (9.0%)
	Manager	69 (36.7%)
	Engineer	27 (14.4%)
	Other	16 (8.5%)

Table 4.3 (cont.)

Sample	Characteristic	Frequency (Percentage)
Technical Sample (n=169)	**Number of Employees:**	not asked
	Annual Sales:	not asked
	Industry:	Frequency (Percentage)
	Aerospace	27 (16.0%)
	Fabricated Metal Product Manufacturing	26 (15.4%)
	Electrical Equip., Appliance and Component Mfg.	23 (13.6%)
	Transportation Equipment Manufacturing	20 (11.8%)
	Miscellaneous Manufacturing	11 (6.5%)
	Computer and Electronic Product Manufacturing	10 (5.9%)
	Primary Metal Manufacturing	7 (4.1%)
	Machinery Manufacturing	6 (3.6%)
	Plastic and Rubber Products Manufacturing	5 (3.0%)
	Other	34 (20.1%)
	Respondent Title:	Frequency (Percentage)
	President / CEO	4 (2.4%)
	Vice President / COO	10 (5.9%)
	Director	9 (5.3%)
	Manager	42 (24.9%)
	Engineer	77 (45.6%)
	Other	27 (16.0%)
Paired Sample (n=94)	**Number of Employees:**	Median=363
	Annual Sales:	Median=$80 Million (US)
	Industry:	Frequency (Percentage)
	Fabricated Metal Product Manufacturing	18 (19.1%)
	Aerospace	14 (14.9%)
	Electrical Equip., Appliance and Component Mfg.	11 (11.7%)
	Transportation Equipment Manufacturing	10 (10.6%)
	Primary Metal Manufacturing	8 (8.5%)
	Computer and Electronic Product Manufacturing	7 (7.4%)
	Machinery Manufacturing	6 (6.4%)
	Miscellaneous Manufacturing	6 (6.4%)
	Plastic and Rubber Products Manufacturing	4 (4.3%)
	Other	10 (10.6%)
	Respondent Title (n=121 due to dual respondents for 27 cases):	Frequency (Percentage)
	President / CEO	6 (5.0%)
	Vice President / COO	13 (10.7%)
	Director	10 (8.3%)
	Supply Chain Lead (or equivalent)	7 (5.8%)
	Manager	42 (34.7%)
	Engineer	32 (26.4%)
	Other	11 (9.0%)

4.7.0 Management of Missing Data

Because missing data can create issues for the application of the statistical methods adopted for analysis, a data imputation procedure was implemented. The Expectation-Maximization (EM) method of imputation was selected due to its ability to produce reliable estimates of missing data for situations where responses are missing at a relatively low rate (Hair et al., 2006). This is the case for the data analyzed in this study, as less than 10% of responses are missing on over 90% of the items selected for study from the retained observations. EM's use, however, is only advisable in situations where the data can be considered Missing Completely at Random (MCAR). Little's MCAR test was used to assess the viability of the EM imputation procedure. In all three samples to be analyzed (Managerial, Technical and Paired), the data was considered to be MCAR, as evidenced by failure to reject the null hypothesis of the data being MCAR at the 10% significance level. As such, EM was used to impute values for missing responses in each sample.

4.8.0 Chapter Summary

This chapter discussed the methods used to obtain the data to be analyzed in order to address the research questions posed for study. An empirical analysis employing perceptual measures of key variables and constructs was selected as an appropriate and efficient means of carrying out the study. A questionnaire was developed and deployed to collect data primarily from firms that produce technically complex products. Three samples were generated from the data collected: 1) a sample containing responses to questions of a technical nature; 2) a sample containing responses to questions that are managerial in nature; and 3) a sample containing observations from organizations that responded to both technical and managerial sections of the questionnaire. Preliminary analysis of the data revealed no evidence of non-response bias, and no discernable pattern to missing data. Values were imputed for missing data in order to produce complete datasets to be used for the assessment of measurement properties and the testing of hypotheses.

5.0.0 Measurement

It has been argued, both in Chapter 2 of this study and in recent scholarly works (Salvador, 2007; Choi & Krause, 2006), that Modularity and Complexity are multi-dimensional constructs, meaning that the latent concepts of interest are comprised of more than one distinct, measurable element. This study assesses the viability of employing a multi-dimensional measurement approach by first establishing the psychometric properties of each proposed dimension of the study constructs, and subsequently testing statistical models that assess the level of association of each dimension with the underlying theoretical construct.

The psychometric properties of each dimension are assessed according to the recommendations for establishing construct validity via Confirmatory Factor Analysis (CFA) proposed by O'Leary-Kelly and Vokurka (1998), and tests for association of each dimension with its underlying construct are performed using the Multiple-Indicator and Multiple-Causes (MIMIC) model of Joreskog and Goldbeger (1975). A MIMIC model positions sets of observed values as both causes and reflective indicators of a latent construct in order to identify the model and estimate the parameters of interest.

5.1.0 Product Modularity

Theoretically, the Product Modularity construct is composed of three dimensions: Functional Binding, Interface Standardization, and Decomposability, as defined in Chapter 2. An initial CFA containing multi-item measures for these three dimensions, as well as for Process Heterogeneity and Process Interdependence (dimensions of Process Complexity) was performed. The data fit the model well according to the cutoff criteria for covariance structure modeling suggested by Hu and Bentler (1999) for samples with less than 250 observations, with CFI=0.963 and SRMR=0.052. However, the dimensions of Product Modularity failed to meet the requirement of Discriminant Validity. Functional Binding exhibited an estimated correlation near 1.00 with Decomposability, and a correlation of 0.99 with Interface Standardization. These results suggest that Function Binding as a dimension cannot be distinguished from Decomposability or Interface Standardization from a statistical standpoint. This condition also invalidates the model, due to the presence of zero and negative error variances, which violate key assumptions of covariance structure modeling. Results for the initial CFA (CFA-01) are summarized in Table 5.1.

Table 5.1: CFA-01 – Dimensions of Product Modularity and Process Complexity

	Scale (Reliability) / *Question*	Std. Loading
	Functional Binding (0.720)	
PD-FB1	*For our products, we can make changes in components without changing other components.*	0.625**
PD-FB2	*For our products, functions can be directly added or deleted by adding or removing components.*	0.682**
PD-FB3	*Our product design is such that a given product function is performed by a single product component.*	Dropped
PD-FB4	*Our products have interchangeable features and options.*	0.735**

Table 5.1 (cont.)

	Interface Standardization (0.775)	
PD-IS1	*Our product components have standardized interfaces.*	0.519**
PD-IS2	*The interfaces of our product components are designed to accept a variety of components.*	0.887**
PD-IS3	*Our product components are able to accept a wide range of complements (such as modules or peripherals).*	0.824**
PD-IS4	*Each component interface is unique. (reversed item)*	Dropped
	Decomposability (0.700)	
PD-DC1	*Our products can be decomposed into separate modules.*	0.556**
PD-DC2	*Our products are designed to be easily disassembled and reassembled.*	0.535**
PD-DC3	*Our products are designed to be easily reconfigured.*	0.853**
	Process Interdependence (0.836)	
PC-INT1	*Our production processes are broken down into sub-processes that can operate independently. (reversed item)*	0.653**
PC-INT2	*Sub-processes can be added to or removed from our production processes without changing other sub-processes. (reversed item)*	0.881**
PC-INT3	*Our production processes are designed so that sub-processes can be added or removed without significant disruptions/changes to other sub-processes. (reversed item)*	0.852**
	Process Heterogeneity (r = 0.387**)	
PC-HTR1	*The products we make have similar processing and assembly requirements. (reversed item)*	0.534**
PC-HTR2	*Only minor equipment modifications are required to produce different products. (reversed item)*	0.718**
PC-HTR3	*We are frequently forced to make changes in our manufacturing processes to satisfy differing customer requirements.*	Dropped
	Fit Statistics: Chi-Square=103.5, df=67; CFI=0.963; GFI=0.921; SRMR=0.053; RMSEA=0.057	**p<0.05

Results from the initial CFA suggest that although the dimensions of Product Modularity are distinguishable from a theoretical standpoint, they may actually form a single dimension statistically. Thus, an alternate measurement approach, which positions all eleven original items reflective items of a single modularity construct, is tested in CFA-02. Although all items loaded significantly on the modularity construct, six items were retained in order to improve model

parsimony and fit. Only items with a factor loading of 0.700 or higher were retained, although careful consideration was made to ensure that the all three theoretical dimensions of modularity were represented in its measurement. This measurement model, which also contains two other constructs measured with data from the technical sample (Process Heterogeneity and Process Interdependence), exhibited a good fit to the data according to the Hu and Bentler (1999) criteria, with CFI=0.953 and SRMR=0.048. In addition, the requirements of Unidimensionality are met through the significant loadings of all items on their respective constructs and the acceptable fit of the overall model, and Convergent and Discriminant Validity are satisfied through the detection of significant differences in the chi-square statistic for the null model versus the measurement model ($\chi^2_{diff,0}$=849.5, df=14, p≈0.00), and the constrained model (covariances of constructs constrained to 1.0) and the measurement model ($\chi^2_{diff,1}$=254.0, df=3, p≈0.00). The reliability of each construct/dimension was assessed via Cronbach's Alpha (Cronbach, 1951). Reliability for Product Modularity and Process Interdependence are 0.907 and 0.836 respectively, well above the minimum acceptable limit of 0.600 for new scales (Nunnally, 1978). However, calculation of Cronbach's Alpha for Process Heterogeneity was precluded due to the retention of only two measurement items. Pearson correlation was calculated for the Process Heterogeneity construct as a surrogate measure of reliability (r = 0.387). Results for CFA-02 are summarized in Table 5.2.

Table 5.2 CFA-02 –Product Modularity and Dimensions of Process Complexity

	Scale (Reliability) / *Question*	Std. Loading
	Product Modularity (0.907)	
PD-MOD1	*Our products are designed to enable the swapping of components.*	0.720**
PD-FB1	*For our products, we can make changes in components without changing other components.*	Dropped
PD-FB2	*For our products, functions can be directly added or deleted by adding or removing components.*	0.706**
PD-FB3	*Our product design is such that a given product function is performed by a single product component.*	Dropped
PD-FB4	*Our products have interchangeable features and options.*	0.768**
PD-IS1	*Our product components have standardized interfaces.*	Dropped
PD-IS2	*The interfaces of our product components are designed to accept a variety of components.*	0.846**
PD-IS3	*Our product components are able to accept a wide range of complements (such as modules or peripherals).*	0.818**
PD-IS4	*Each component interface is unique. (reversed item)*	Dropped
PD-DC1	*Our products can be decomposed into separate modules.*	Dropped
PD-DC2	*Our products are designed to be easily disassembled and reassembled.*	Dropped
PD-DC3	*Our products are designed to be easily reconfigured.*	0.768**
	Process Interdependence (0.836)	
PC-INT1	*Our production processes are broken down into sub-processes that can operate independently. (reversed item)*	0.653**
PC-INT2	*Sub-processes can be added to or removed from our production processes without changing other sub-processes. (reversed item)*	0.881**
PC-INT3	*Our production processes are designed so that sub-processes can be added or removed without significant disruptions/changes to other sub-processes. (reversed item)*	0.852**
	Process Heterogeneity (r = 0.387**)	
PC-HTR1	*The products we make have similar processing and assembly requirements. (reversed item)*	0.518**
PC-HTR2	*Only minor equipment modifications are required to produce different products. (reversed item)*	0.741**
PC-HTR3	*We are frequently forced to make changes in our manufacturing processes to satisfy differing customer requirements.*	Dropped
	Fit Statistics: Chi-Square=82.1, df=41; CFI=0.953; GFI=0.916; SRMR=0.048; RMSEA=0.078	**p<0.05

Due to the inability to distinguish among the dimensions of the modularity construct, and because a valid one dimensional measure of modularity has been established, analysis of the associations of each dimension to the underlying construct via MIMIC is precluded.

5.2.0 Complexity

Complexity, as discussed in Chapter 2, is theoretically composed of three dimensions: Number of Elements, Heterogeneity, and Interdependence. Each of the three types of complexity: Manufacturing Process Complexity, Organizational Complexity, and Supply Base Complexity, are examined to assess the composition of the construct in terms of the theoretical dimensions of complexity, and to establish valid and reliable measures of each construct.

5.2.1 Process Complexity

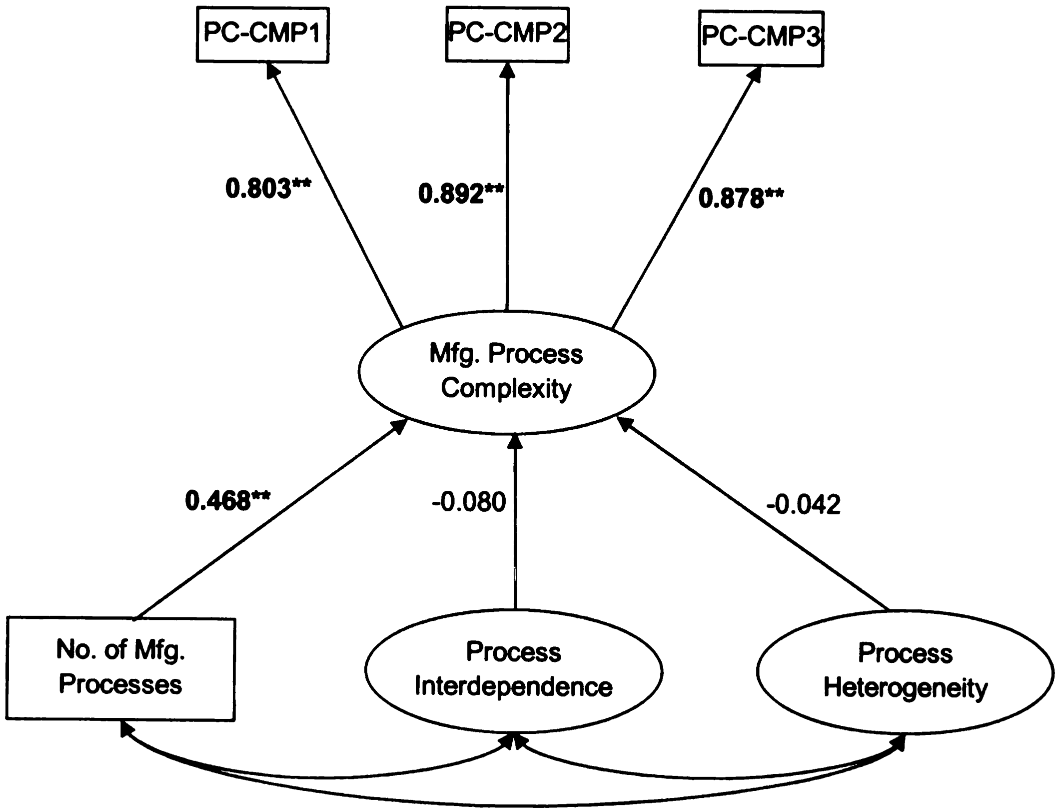
As shown in CFA-02 (Table 5.2), the two dimensions of Process Complexity that are captured with multi-item measures, Process Heterogeneity and Process Interdependence, are distinct and exhibit reasonable psychometric properties. The remaining dimension, Number of Elements, was captured with a single objective response item asking respondents to report the number of internal manufacturing processes used to manufacture their primary products.

A MIMIC model was fit to the data to examine the association of the Number of Internal Manufacturing Processes, Process Heterogeneity, and Process

Interdependence to the Manufacturing Process Complexity Construct (Figure 5.1). Three items purported to measure the Process Complexity construct directly were included to identify the model (PC-CMP1, PC-CMP2, PC-CMP3). The model did not exhibit a very strong fit to the data, with CFI=0.944 and SRMR=0.089. In addition, only the Number of Internal Manufacturing Processes was significantly related to the Process Complexity construct.

The results of the MIMIC model analysis suggest that Manufacturing Process Complexity cannot be reliably measured as a composite of its theoretically derived dimensions as they have been measured for this study. As such, the examination proceeded to establishing the measurement properties of the direct Manufacturing Process Complexity measurement items. CFA-03 (Table 5.3) includes the Manufacturing Complexity Construct as measured by these items. This model displays a good fit to the data, with CFI=0.962 and SRMR=0.051. Conditions of Unidimensionality, Convergent Validity and Discriminant Validity are met with significant factor loadings of all included items, and significant chi-square differences statistics between the null model and the measurement model ($\chi^2_{diff,0}$=828.6, df=10, $p \approx 0.00$), as well as between the constrained model and the measurement model ($\chi^2_{diff,1}$=287.9, df=1, $p \approx 0.00$). The Manufacturing Process Complexity construct also exhibits good reliability, with an alpha value of 0.893.

Figure 5.1 Manufacturing Process Complexity MIMIC Model



Fit Statistics:
Chi-Square=58.617, df=22; CFI=0.944; GFI=0.924;
SRMR=0.089; RMSEA=0.100

*Notes: **p<0.05*

Table 5.3 CFA-03 –Product Modularity and Process Complexity

	Scale (Reliability) / *Question*	Std. Loading
	Product Modularity (0.907)	
PD-MOD1	*Our products are designed to enable the swapping of components.*	0.719**
PD-FB1	*For our products, we can make changes in components without changing other components.*	Dropped
PD-FB2	*For our products, functions can be directly added or deleted by adding or removing components.*	0.708**
PD-FB3	*Our product design is such that a given product function is performed by a single product component.*	Dropped
PD-FB4	*Our products have interchangeable features and options.*	0.762**
PD-IS1	*Our product components have standardized interfaces.*	Dropped
PD-IS2	*The interfaces of our product components are designed to accept a variety of components.*	0.850**
PD-IS3	*Our product components are able to accept a wide range of complements (such as modules or peripherals).*	0.823**
PD-IS4	*Each component interface is unique. (reversed item)*	Dropped
PD-DC1	*Our products can be decomposed into separate modules.*	Dropped
PD-DC2	*Our products are designed to be easily disassembled and reassembled.*	Dropped
PD-DC3	*Our products are designed to be easily reconfigured.*	0.761**
	Manufacturing Process Complexity (0.893)	
PC-CMP1	*Our production system is very sophisticated in terms of its operating characteristics.*	0.808**
PC-CMP2	*Our production system is very complex.*	0.883**
PC-CMP3	*Our production system is very sophisticated in terms of structure/layout.*	0.884**
	Fit Statistics: Chi-Square=58.7, df=26; CFI=0.962; GFI=0.927; SRMR=0.051; RMSEA=0.087	**p<0.05

5.2.2 Organizational Complexity

The individual dimensions of the Organizational Complexity construct (Organizational Heterogeneity and Organizational Interdependence) were analyzed along with dimensions of Supply Base Complexity (Supply Base Heterogeneity and Supply Base Interdependence) and Environmental Uncertainty in CFA-04 (Table 5.4). This measurement model exhibited a good fit to the data, with CFI=0.956 and SRMR=0.049. All factor loadings are significant, indicating satisfactory Unidimensionality, and Convergent and Discriminant Validity conditions are satisfied, as illustrated by significant chi-square difference statistics for the comparison of the null model and the measurement model ($\chi^2_{diff,0}$=908.0, df=26, p≈0.00), and the constrained model and measurement model ($\chi^2_{diff,1}$=374.6, df=10, p≈0.00). Scale reliabilities are also acceptable, with alphas of 0.807, 0.720, 0.802, and 0.753 for Organizational Interdependence, Organizational Heterogeneity, Environmental Uncertainty and Supply Base Interdependence respectively. Calculation of Cronbach's Alpha for Supply Base Heterogeneity was precluded because the construct was measured with only two items. Pearson correlation was calculated for the Supply Base Heterogeneity construct as a surrogate measure of reliability (r = 0.362).

Table 5.4 CFA-04 – Environmental Uncertainty and Dimensions of Organizational Complexity and Supply Base Complexity

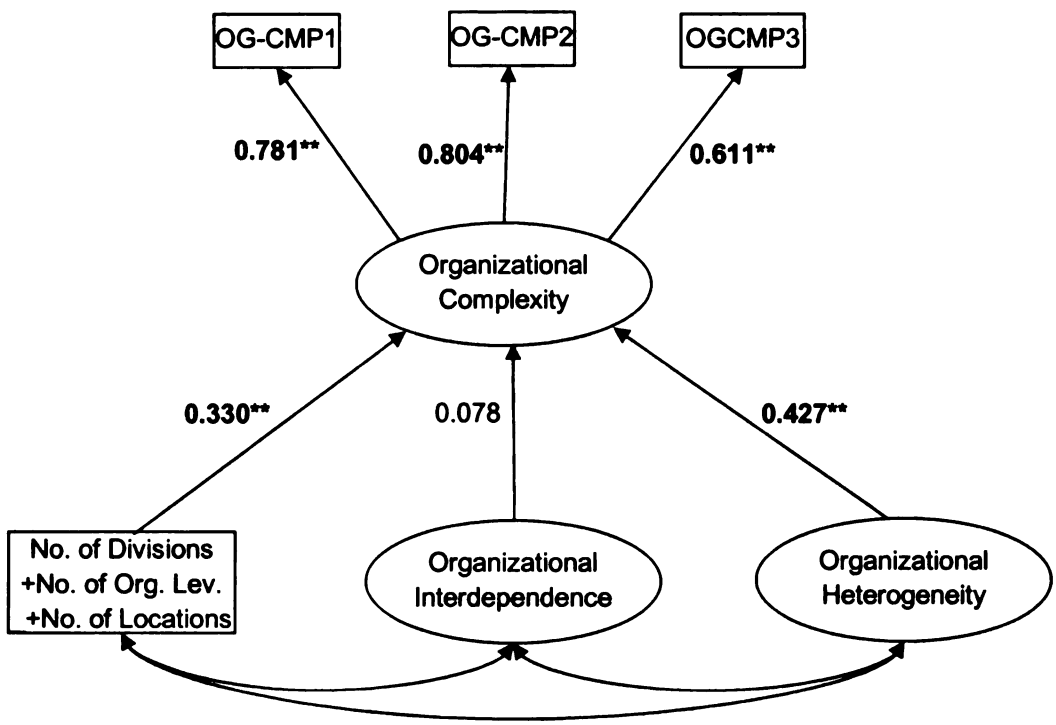
	Scale (Reliability) / *Question*	Std. Loading
	Organizational Heterogeneity (0.807)	
OG-HTR1	*Sub-units in our firm/SBU are subject to the same policies (ex.: quality standards, compensation, absenteeism, etc.). (reversed item)*	0.742**
OG-HTR2	*Sub-units in our firm/SBU employ similar or compatible business practices. (reversed item)*	0.778**
OG-HTR3	*Sub-units in our firm/SBU have similar or compatible information systems/technologies. (reversed item)*	0.683**
OG-HTR4	*Sub-units in our firm/SBU use common mechanisms for coordinating work. (reversed item)*	0.670**
OG-HTR5	*The organizational structures of sub-units in our firm/SBU are similar. (reversed item)*	Dropped
	Organizational Interdependence (0.720)	
OG-INT1	*Project teams are self-directed. (reversed item)*	0.601**
OG-INT2	*Project teams operate autonomously. (reversed item)*	Dropped
OG-INT3	*Project teams operate independently from other organizational entities. (reversed item)*	Dropped
OG-INT4	*Project teams are free to develop links with other teams and/or internal units in our firm/SBU. (reversed item)*	0.845**
OG-INT5	*Project teams are free to develop links with external units such as suppliers, customers, etc. (reversed item)*	0.616**
	Environmental Uncertainty (0.802)	
EN-UNC1	*Sales forecasts for our primary products are likely to be: (very inaccurate…very accurate)*	Dropped
EN-UNC2	*Predicting the actions of our competitors is: (very easy…very difficult)*	0.635**
EN-UNC3	*Predicting consumer tastes in our market(s) is: (very easy…very difficult)*	0.797**
EN-UNC4	*Monitoring market trends for our primary products is: (very easy…very difficult)*	0.758**
EN-UNC5	*Predicting demand for our primary product line is: (very easy…very difficult)*	0.664**
	Supply Base Interdependence (0.753)	
SB-INT1	*We have frequent face-to-face communication with key suppliers.*	0.611**
SB-INT2	*For a given supplier, there are multiple points of contact between our organization and the supplier's.*	Dropped
SB-INT3	*We have long-term relationships with our suppliers.*	0.794**
SB-INT4	*We have strong ties to our suppliers.*	0.759**

Table 5.4 (cont.)

	Supply Base Heterogeneity (r = 0.362**)	
SB-HTR1	*Our suppliers are diverse in terms of size, location, and products supplied.*	0.632**
SB-HTR2	*Effective management of procurement requires taking different approaches with different suppliers.*	0.573**
	Fit Statistics: Chi-Square=146.4, df=94; CFI=0.944; GFI=0.915; SRMR=0.049; RMSEA=0.055	**p<0.05

A second MIMIC model was fitted to examine the association of Organizational Complexity with its theoretical dimensions (Figure 5.2). The Number of Elements dimension for Organizational Complexity is represented by the sum of three objective response items: (1) the number of organizational divisions; (2) the number of organizational levels; (3) the number of worldwide locations. Three direct measures of Organizational Complexity (OG-CMP1, OG-CMP2, OG-CMP3) were included to identify the model. The model exhibited a poor fit to the data, with CFI=0.892 and SRMR=0.075. However, both the Number of Organizational Elements and Organizational Heterogeneity were significantly related to the Organizational Complexity construct in this model.

Figure 5.2 Organizational Complexity MIMIC Model



Fit Statistics:
Chi-Square=111.751, df=39; CFI=0.892; GFI=0.910;
SRMR=0.075; RMSEA=0.101

*Notes: **p<0.05*

As was the case with Manufacturing Process Complexity, Organizational Complexity was not measured reliably as a composite of its theoretical dimensions as they have been measured for this study. Consequently, the examination of the psychometric properties of the direct Organizational Complexity measures followed. CFA-05 (Table 5.5) substitutes the Organizational Complexity construct as measured by the direct items for the individual dimensions of Organizational Complexity in CFA-04. The model exhibited a fair fit to the data, with a CFI=0.915 and SRMR=0.073. Unidimensionality, Convergent Validity and Discriminant Validity were all satisfied

($\chi^2_{diff,0}$=607.8, df=18, p≈0.00; $\chi^2_{diff,1}$=382.4, df=6, p≈0.00). Reliability for the Organizational Complexity is acceptable, with an estimated alpha of 0.763.

Table 5.5 CFA-05 –Environmental Uncertainty, Organizational Complexity and Dimensions of Supply Base Complexity

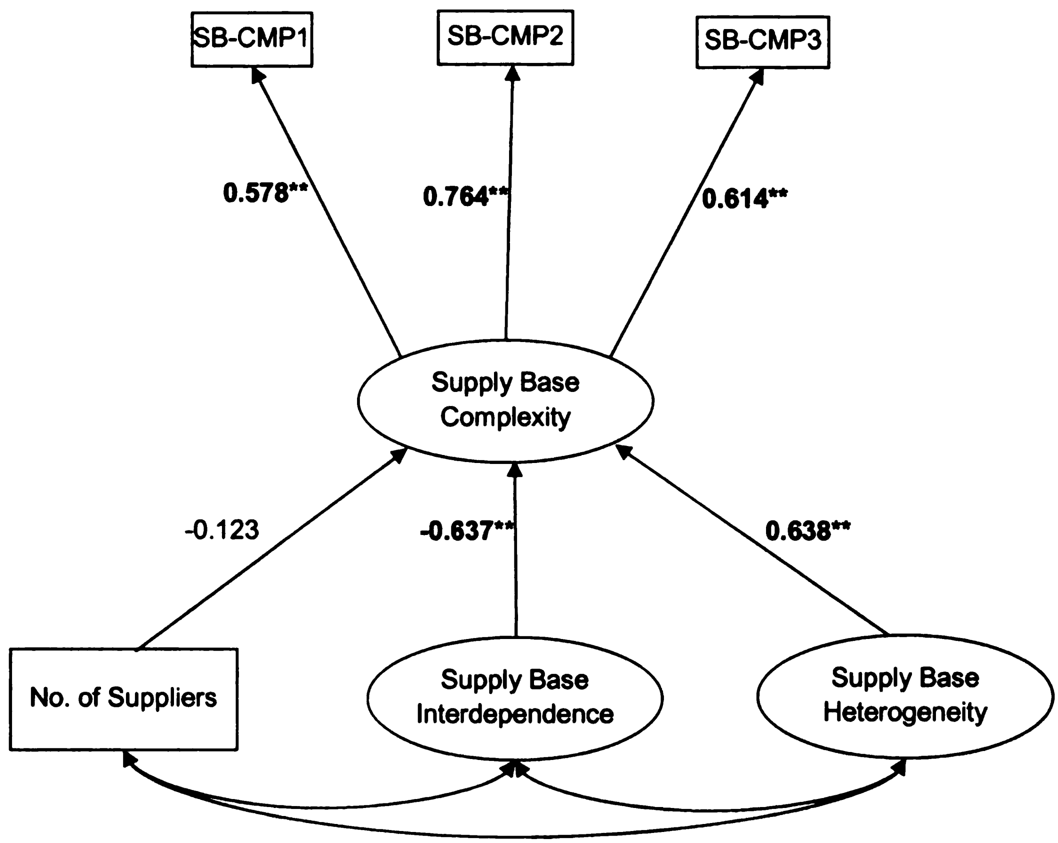
	Scale (Reliability) / *Question*	Std. Loading
	Organizational Complexity (0.763)	
OG-CMP1	*Our firm/SBU has a very complex organizational structure.*	0.842**
OG-CMP2	*Our firm/SBU is organized in a straight-forward, uncomplicated way. (reversed item)*	0.754**
OG-CMP3	*Coordinating work between sub-units in our firm/SBU is difficult.*	0.606**
	Environmental Uncertainty (0.802)	
EN-UNC1	*Sales forecasts for our primary products are likely to be: (very inaccurate…very accurate)*	Dropped
EN-UNC2	*Predicting the actions of our competitors is: (very easy…very difficult)*	0.633**
EN-UNC3	*Predicting consumer tastes in our market(s) is: (very easy…very difficult)*	0.797**
EN-UNC4	*Monitoring market trends for our primary products is: (very easy…very difficult)*	0.759**
EN-UNC5	*Predicting demand for our primary product line is: (very easy…very difficult)*	0.663**
	Supply Base Interdependence (0.753)	
SB-INT1	*We have frequent face-to-face communication with key suppliers.*	0.589**
SB-INT2	*For a given supplier, there are multiple points of contact between our organization and the supplier's.*	Dropped
SB-INT3	*We have long-term relationships with our suppliers.*	0.824**
SB-INT4	*We have strong ties to our suppliers.*	0.745**
	Supply Base Heterogeneity (r = 0.362**)	
SB-HTR1	*Our suppliers are diverse in terms of size, location, and products supplied.*	0.692**
SB-HTR2	*Effective management of procurement requires taking different approaches with different suppliers.*	0.523**
	Fit Statistics: Chi-Square=87.0, df=48; CFI=0.938; GFI=0.930; SRMR=0.058; RMSEA=0.066	**p<0.05

5.2.3 Supply Base Complexity

The dimensions of Supply Base Complexity (Supply Base Heterogeneity and Supply Base Interdependence) were included in both CFA-04 and CFA-05 and exhibited reasonable measurement properties (see tables 5.4 and 5.5). The Number of Elements dimension for Supply Base Complexity was measured with a single objective response item asking respondents to report the approximate number of suppliers used by their firm or SBU.

A third MIMIC model examining the association of Supply Base Complexity to its proposed dimensions was fit to the data (Figure 5.3). As in prior MIMIC analyses, three direct measures of Supply Base Complexity were included to identify the model. The model fit was poor, with CFI=0.899 and SRMR=0.070, however, Supply Base Heterogeneity and Supply Base Interdependence were significantly related to the construct, although the path coefficient from Supply Base Interdependence was negative.

Figure 5.3 Supply Base Complexity MIMIC Model



Fit Statistics:
Chi-Square=57.422, df=22; CFI=0.899; GFI=0.936;
SRMR=0.070; RMSEA=0.094

*Notes: **p<0.05*

Similar to the cases of Organizational Complexity and Manufacturing Process Complexity, Supply Base Complexity was not reliably measured as a composite of its theoretical dimensions as they have been measured for this study. Hence, measurement with items that tap Supply Base Complexity directly (SB-CMP1, SB-CMP2, SB-CMP3) was evaluated for validity and reliability. The measurement model (CFA-06, Table 5.6) exhibited a fair fit to the data, with CFI=0.943 and SRMR=0.061. Constructs measured in this model met the criteria of Unidimensionality, Convergent Validity and Discriminant Validity ($\chi^2_{diff,0}$=748.8, df=20, p≈0.00; $\chi^2_{diff,1}$=365.0, df=6, p≈0.00), and the alpha reliability estimate for Supply Base Complexity was acceptable at 0.672.

Table 5.6 CFA-06 – Environmental Uncertainty, Organizational Complexity and Supply Base Complexity

	Scale (Reliability) / *Question*	Std. Loading
	Organizational Complexity (0.763)	
OG-CMP1	*Our firm/SBU has a very complex organizational structure.*	0.842**
OG-CMP2	*Our firm/SBU is organized in a straight-forward, uncomplicated way. (reversed item)*	0.754**
OG-CMP3	*Coordinating work between sub-units in our firm/SBU is difficult.*	0.606**
	Environmental Uncertainty (0.802)	
EN-UNC1	*Sales forecasts for our primary products are likely to be: (very accurate…very inaccurate)*	Dropped
EN-UNC2	*Predicting the actions of our competitors is: (very easy…very difficult)*	0.633**
EN-UNC3	*Predicting consumer tastes in our market(s) is: (very easy…very difficult)*	0.797**
EN-UNC4	*Monitoring market trends for our primary products is: (very easy…very difficult)*	0.759**
EN-UNC5	*Predicting demand for our primary product line is: (very easy…very difficult)*	0.663**
	Supply Base Complexity (0.672)	
SB-CMP1	*Coordinating procurement and manufacturing operations is problematic for our firm/SBU.*	0.602**
SB-CMP2	*The structure of our supply chain is difficult to describe or illustrate.*	0.799**
SB-CMP3	*Our supply chain is a very complex network.*	0.538**
	Fit Statistics: Chi-Square=124.5, df=71; CFI=0.932; GFI=0.914; SRMR=0.059; RMSEA=0.063	**p<0.05

5.3.0 Chapter Summary

In this chapter, an assessment was performed of the viability of multi-dimensional measurement approaches for the constructs under study: (1) Product Modularity, (2) Manufacturing Process Complexity, (3) Organizational Complexity, and (4) Supply Base Complexity. The results indicate that only the Product Modularity construct could be measured validly and reliably employing all theoretically derived dimensions, albeit the theoretical dimensions of the construct were all reflected in a single dimension statistically.

Each theoretically derived dimension of complexity showed a significant association with complexity on at least one organizational level (i.e., manufacturing process, organization, or supply base), but in no case were all three dimensions significantly linked to a complexity construct. Instead, reliable and valid measures of each type of complexity were obtained by tapping the construct directly, as opposed to measuring its constituent dimensions. The next chapter discusses the procedures used to test the hypotheses presented in Chapter 3.

6.0.0 Hypothesis Testing

In this chapter, hypotheses are tested which relate variables measured in the technical section of the survey to variables measured in the managerial section of the survey. Hence, only those cases for which both sections of the questionnaire received responses are observed (n=94). The lower sample size precludes the straight-forward application of common multivariate methods for analyzing relationships among latent variables (such as Structural Equation Modeling - SEM). Therefore analysis will proceed employing summated scales of the measures that were validated using the larger samples in Chapter 5, and Seemingly Unrelated Regression (SUR) – an econometric method of analyzing systems of equations that is less restrictive than SEM in terms of required sample size. The use of summated scales is an acceptable alternative means of representing latent constructs in multivariate analysis, provided that they meet the requirements of validity and reliability (Hair Jr., Black, Babin, Anderson, & Tatham, 2006), as demonstrated in Chapter 5.

6.1.0 Pairing of Responses

Of the 94 cases analyzed, 27 cases are paired responses from different individuals within the same organization. The remaining 67 responses were cases where a single individual responded to both the technical and managerial sections of the questionnaire. The average Intraclass Correlation Coefficient (ICC) was used to assess the level of agreement in responses provided by different individuals from the same organization. The computed value for the average ICC on four performance items for which different individuals within the same organization responded was 0.58, just below the minimum threshold for agreement of 0.60 recommended by Boyer and Verma (2000) for Operations Management and Strategy research. Although the minimum threshold for agreement was not exceeded, the decision was made to proceed with the pairing of matched responses because: (1) they constitute a relatively low proportion of the sample (29%); and (2) the measures of interest in this study were not asked of both respondents.

6.2.0 Seemingly Unrelated Regression (SUR)

Seemingly Unrelated Regression (Zellner, 1962) is an econometric technique of efficiently estimating parameters of sets of equations that appear to be independent (i.e., they do not exhibit simultaneity – having variables that are exogenous with respect to one equation in the set, but endogenous in another), but may exhibit error correlation across equations. The SUR model uses a Feasible Generalized Least Squares (FGLS) approach to correct for error correlation across equations and produces more efficient parameter estimates than OLS (Kennedy, 2003).

Because SUR first performs Ordinary Least Squares (OLS) regression on the individual equations, and subsequently uses the residuals to produce estimates of variances and covariances, it does not require as large a sample to produce consistent parameter estimates as SEM. It only requires that the number of observations used to estimate each equation be larger than the number of equations. However to produce reliable estimates, it is recommended that the number of observations be "quite large" compared to the number of equations (Kennedy, 2003). Like OLS regression, the conditions of the Gauss-Markov Theorem (excluding the requirement of spherical disturbances, which the SUR model corrects for) must be met to produce the best linear unbiased estimates. In addition, because the SUR model estimates a system of equations, order and rank conditions must also be met in order for the model to be identified.

Seemingly Unrelated Regression uses the same goodness of fit measures as OLS for overall model fit: the F-test for lack of fit and the Coefficient of Determination, R^2. The F-test evaluates the null hypothesis that all regression coefficients in the model are jointly equal to zero, while the Coefficient of Determination offers an estimate of the proportion of variance in the dependent variable that is explained by the independent variables. SUR estimates an F-statistic and Coefficient of Determination for each equation in the model. Evaluation of the statistical significance of an individual regression coefficient is performed via the t-statistic, just as in OLS regression.

The SUR model is an appropriate technique for hypothesis testing in this study because each observation in the set of equations to be estimated represents a production system, in which the constituent parts operate together in the creation of products. Therefore it can be assumed that the equations to be estimated are not independent; hence their error terms may be correlated. In addition, the lower sample size requirement makes SUR an attractive choice for hypothesis testing here, especially when considering the need to parse the sample in order to test for the hypothesized contingency and moderating effects of System Openness and Environmental Uncertainty.

6.3.0 Preliminary Analysis

Prior to hypothesis testing, preliminary diagnostics were run on the data. Bivariate scatterplots of the dependent variables versus the independent variables were produced in order to detect outlying observations. This procedure identified six (6) outliers. Upon careful review of the characteristics of these observations, they were excluded from further analysis. Descriptive statistics for the study variables are included in Table 6.1.

Table 6.1: Descriptive Statistics for Model Constructs

Construct	**Mean**	**Standard Deviation**
Product Modularity *(6 items, 7-point scales)*	22.50	9.57
Mfg. Process Complexity *(3 items, 7-point scales)*	12.93	4.02
Organizational Complexity *(3 items, 7-point scales)*	9.56	3.77
Supply Base Complexity *(3 items, 7-point scales)*	10.04	3.51

Table 6.1 (cont)

Outsourcing *(1 item, 7-point scale)*	3.16	1.81
Environmental Uncertainty *(4 items, 7-point scales)*	17.22	3.89
Number of Mfg. Processes *(1 item, 7-point scale)*	4.13	1.95
Number of Org. Divisions *(1 item, 7-point scale)*	2.83	2.06
Number of Suppliers *(1 item, 7-point scale)*	3.32	1.59

6.4.0 Results

The SUR Model analyzed for hypothesis testing is defined as follows:

(1) $COMPLEXITY_{process} = \beta_o + \beta_1{*}MODULARITY_{product} + \beta_2{*}NUMBER_{mfgprocesses} + \varepsilon$

(2) $COMPLEXITY_{org} = \beta_o + \beta_1{*}MODULARITY_{product} + \beta_2{*}NUMBER_{orgdivisions} + \varepsilon$

(3) $COMPLEXITY_{supplybase} = \beta_o + \beta_1{*}MODULARITY_{product} + \beta_2{*}NUMBER_{suppliers} + \varepsilon$

The *i* subscript representing individual observations has been dropped from each variable and error term for simplification.

The COMPLEXITY terms on the left-hand side of each equation above represent the dependent variables: Manufacturing Process Complexity, Organizational Complexity, and Supply Base Complexity. The MODULARITY terms or the right-hand side of equation above represent the primary independent variable, Product Modularity. The NUMBER variables in the model above (Number of

Manufacturing Processes, Number of Organizational Divisions, and Number of Suppliers) function as instrumental variables, aiding in the identification of the model and controlling for potential simultaneity.

6.4.1 Exploratory Model

Hypotheses one (H1) through three (H3) were tested by fitting the SUR model above to the full sample, absent the outliers purged in preliminary analysis (n=88). Results are summarized in Table 6.2 below. Equations (1) and (3) exhibited a good fit to the data, with significant F-statistics ($p < 0.05$) and R^2 values of 0.15 and 0.13 respectively. Equation (2) did not exhibit a good fit to the data, with a nonsignificant F-statistic (p=0.262) and an R^2 value of 0.04.

Table 6.2: SUR Exploratory Model – Full Sample (n=88)

Goodness of Fit Measures				
Equation #	Dependent Variable	R^2	F-statistic	p-value
(1)	Process Complexity	0.1519	**7.11**	**0.001**
(2)	Organizational Complexity	0.0442	1.35	0.262
(3)	Supply Base Complexity	0.1301	**4.75**	**0.009**
Parameter Estimates				
	Coefficient	Standard Error	t-statistic	p-value
Equation (1) Process Complexity				
Constant	**8.597**	**1.254**	**6.86**	**0.000**
Product Modularity	0.080	0.041	1.93	0.055
No of Mfg. Processes	**0.615**	**0.202**	**3.04**	**0.003**

Table 6.2 (cont.)

	Coefficient	Standard Error	t-statistic	p-value
Equation (2) Org. Complexity				
Constant	**8.139**	**1.041**	**7.82**	**0.000**
Product Modularity	0.038	0.042	0.90	0.366
No. of Divisions	0.200	0.176	1.14	0.257
Equation (3) Supply Base Complx.				
Constant	**6.655**	**1.151**	**5.78**	**0.000**
Product Modularity	**0.091**	**0.036**	**2.51**	**0.013**
No. of Suppliers	**0.402**	**0.195**	**2.06**	**0.041**
Breusch-Pagan Test of Independence: Chi-square=20.615, df=3 p=0.000				

Hypothesis one (H1) states that Product Modularity influences the complexity of internal manufacturing processes. This hypothesis was not supported, as the t-statistic on the regression coefficient for Product Modularity in equation (1) was not found to be significant at the 5% alpha level (p=0.055). Hypothesis two (H2) states that Product Modularity influences the complexity of organizational design and coordination. This hypothesis was not supported, as the t-statistic on the Product Modularity regression coefficient in equation (2) was not found to be significant at an alpha level of 0.05 (p=0.366). Hypothesis three (H3) states that Product Modularity influences the complexity of a firm's supply base. This hypothesis was supported, as the t-statistic on the regression coefficient for Product Modularity in equation (3) was found to be significant at the 0.05 alpha level (p=0.013).

6.4.2 Contingency Model

Hypotheses 4a through 6a were tested by fitting the SUR model to a partial sample. The sample of 88 observations was split into two groups based on values of the proxy for system openness – the reported percentage of the components of the firm or SBU's primary products that are outsourced. Values falling below the sample mean of 3.16 (7-point Likert scale with anchors: 1=less than 10% outsourced and 7=more than 85% outsourced) were considered the low-outsourcing or "closed system" group. Fifty-four (54) observations were included in this group. Results of the SUR model estimation for the "closed system" group are summarized in Table 6.3 below. Equation (1) exhibited a good fit to the data for the "closed system" group, with a significant F-statistic (p=0.027) and an R^2 value of 0.12. Equations (2) and (3) did not exhibit good fits to the data, with nonsignificant F-statistics ($p > 0.05$), and low R^2 values, 0.02 and 0.04 respectively.

Table 6.3: SUR Contingency Model – Closed System Sample (n=54)

Goodness of Fit Measures				
Equation #	Dependent Variable	R^2	F-statistic	p-value
(1)	Process Complexity	0.1199	**3.71**	**0.027**
(2)	Organizational Complexity	0.0153	0.23	0.798
(3)	Supply Base Complexity	0.042	0.74	0.477

Table 6.3 (cont.)

Parameter Estimates				
	Coefficient	Standard Error	t-statistic	p-value
Equation (1) Process Complexity				
Constant	**9.067**	**1.671**	**5.43**	**0.000**
Product Modularity	0.027	0.056	0.49	0.622
No of Mfg. Processes	**0.748**	**0.282**	**2.65**	**0.009**
Equation (2) Org. Complexity				
Constant	**9.382**	**1.510**	**6.21**	**0.000**
Product Modularity	-0.001	0.062	-0.02	0.983
No. of Divisions	0.169	0.256	0.66	0.511
Equation (3) Supply Base Complx.				
Constant	**8.190**	**1.460**	**5.61**	**0.000**
Product Modularity	0.055	0.049	1.13	0.262
No. of Suppliers	0.138	0.250	0.55	0.581
Breusch-Pagan Test of Independence: Chi-square=18.666, df=3 p=0.000				

Hypothesis 4a states that in closed systems, Product Modularity is positively associated with the complexity of internal manufacturing systems. This hypothesis was not supported, as the t-statistic on the Product Modularity coefficient for equation (1) was not significant at the 0.05 alpha level (p=0.622). Hypothesis 5a states that in closed systems, Product Modularity is positively associated with the complexity of organizational design and coordination. This hypothesis was not supported, as the t-statistic on the regression coefficient for

Product Modularity in equation (2) was not significant at the 0.05 alpha level (p=0.983). Hypothesis 6a states that in closed systems, Product Modularity is positively associated with the complexity of a firm or SBU's supply base. This hypothesis was not supported, as the t-statistic on the Product Modularity coefficient in equation (3) was not found to be significant at the 0.05 alpha level (p=0.262).

Hypotheses 4b through 6b were tested by fitting the SUR model to the high outsourcing or "open system" group. This group (n=34) is composed of observations whose reported value on the proxy for system openness was above the sample mean of 3.16. Results of the SUR model estimation for the "open system" group are reported in Table 6.4 below. Equation (1) through (3) exhibited good fits to the data, with significant F-statistics ($p < 0.05$), and R^2 values of 0.22, 0.21 and 0.28 respectively.

Table 6.4: SUR Contingency Model – Open System Sample (n=34)

Goodness of Fit Measures				
Equation #	Dependent Variable	R^2	F-statistic	p-value
(1)	Mfg. Process Complexity	0.2191	**4.38**	**0.015**
(2)	Organizational Complexity	0.2088	**3.91**	**0.023**
(3)	Supply Base Complexity	0.2814	**5.47**	**0.006**

Table 6.4 (cont.)

Parameter Estimates				
	Coefficient	Standard Error	t-statistic	p-value
Equation (1) Process Complexity				
Constant	**8.662**	**1.905**	**4.55**	**0.000**
Product Modularity	**0.151**	**0.060**	**2.51**	**0.014**
No of Mfg. Processes	0.343	0.303	1.13	0.260
Equation (2) Org. Complexity				
Constant	**6.137**	**1.261**	**4.87**	**0.000**
Product Modularity	0.075	0.049	1.55	0.124
No. of Divisions	0.417	0.217	1.92	0.058
Equation (3) Supply Base Complx.				
Constant	**4.506**	**1.845**	**2.44**	**0.016**
Product Modularity	**0.140**	**0.053**	**2.62**	**0.010**
No. of Suppliers	**0.744**	**0.310**	**2.40**	**0.018**
Breusch-Pagan Test of Independence: Chi-square=2.385, df=3 p=0.497				

Hypothesis 4b states that in open systems, Product Modularity is negatively related to the complexity of internal manufacturing systems. Although the t-statistic is significant (p=0.014) at the 0.05 alpha level for the Product Modularity coefficient in equation (1), the hypothesis is not supported because the direction of the relationship is counter to what theory predicts. Hypothesis 5b states that in open systems, Product Modularity is negatively related to the complexity of organizational design and coordination. This hypothesis is not supported, as evidenced by a nonsignificant t-statistic (p=0.124) on the Product Modularity

coefficient in equation (2). Hypothesis 6b states that in open systems, Product Modularity is negatively related to the complexity of supply bases. Although the t-statistic on the Product Modularity coefficient in equation (3) is significant at the 0.05 alpha level (p=0.01), the hypothesis is not supported because the direction of the relationship is counter to what theory predicts.

6.4.3 Moderation Model

The final set of hypotheses, H7 through H9, considers the effects of Environmental Uncertainty on the relationship between Product Modularity and Complexity at the three observed organizational levels. These hypotheses conjecture that Environmental Uncertainty has a moderating effect on the relationship. In other words, it is argued that the presence of Environmental Uncertainty affects the strength of the relationship between the study variables. In order to test these hypotheses, the sample was again split into two (2) groups, a high uncertainty group (n=39) and a low uncertainty group (n=49), with the mean value of the summated 4-item Environmental Uncertainty scale (mean = 17.22) serving as the separator. The SUR model was fit to the data for both groups separately, and results of each estimation were compared in order to test hypotheses seven (H7) through nine (H9). Results of the SUR model estimation for the high and low uncertainty groups are summarized in Tables 6.5 and 6.6 below.

Table 6.5: SUR Moderation Model – Low Environmental Uncertainty Sample (n=49)

Goodness of Fit Measures				
Equation #	Dependent Variable	R^2	F-statistic	p-value
(1)	Mfg. Process Complexity	0.1434	**3.18**	**0.045**
(2)	Organizational Complexity	0.0673	0.96	0.386
(3)	Supply Base Complexity	0.1459	2.91	0.058
Parameter Estimates				
	Coefficient	Standard Error	t-statistic	p-value
Equation (1) Process Complexity				
Constant	**10.18**	**1.729**	**5.88**	**0.000**
Product Modularity	0.030	0.048	0.61	0.541
No of Mfg. Processes	**0.602**	**0.241**	**2.49**	**0.014**
Equation (2) Org. Complexity				
Constant	**8.212**	**1.437**	**5.71**	**0.000**
Product Modularity	0.017	0.053	0.32	0.751
No. of Divisions	0.304	0.237	1.28	0.202
Equation (3) Supply Base Complx.				
Constant	**6.312**	**1.806**	**3.50**	**0.001**
Product Modularity	0.073	0.050	1.46	0.146
No. of Suppliers	**0.612**	**0.273**	**2.24**	**0.026**
Breusch-Pagan Test of Independence: Chi-square=12.346, df=3 p=0.006				

Table 6.6: SUR Model – High Environmental Uncertainty Sample (n=39)

Goodness of Fit Measures				
Equation #	Dependent Variable	R^2	F-statistic	p-value
(1)	Mfg. Process Complexity	0.1527	**3.47**	**0.035**
(2)	Organizational Complexity	0.0464	0.92	0.403
(3)	Supply Base Complexity	0.1352	3.06	0.051
Parameter Estimates				
	Coefficient	Standard Error	t-statistic	p-value
Equation (1) Process Complexity				
Constant	**7.554**	**1.850**	**4.08**	**0.000**
Product Modularity	**0.154**	**0.075**	**2.06**	**0.042**
No of Mfg. Processes	0.369	0.369	1.00	0.319
Equation (2) Org. Complexity				
Constant	**7.748**	**1.520**	**5.10**	**0.000**
Product Modularity	0.078	0.069	1.13	0.260
No. of Divisions	0.097	0.260	0.37	0.709
Equation (3) Supply Base Complx.				
Constant	**6.819**	**1.515**	**4.50**	**0.000**
Product Modularity	**0.137**	**0.055**	**2.47**	**0.015**
No. of Suppliers	0.026	0.304	0.08	0.933
Breusch-Pagan Test of Independence: Chi-square=8.541, df=3 p=0.036				

In both groups, equation (1) exhibited a good fit to the data, with significant F-statistics ($p < 0.05$) and R^2 values of 0.14 and 0.15. Equation (3) exhibited a marginal fit to the data in the low and high uncertainty groups with F-statistics of

2.91 (p=0.058) and 3.06 (p=0.051) and R^2 values 0.15 and 0.14 respectively. Equation (2) exhibited a poor fit to the data in both groups with nonsignificant F-statistics ($p >> 0.05$) and R^2 values below 0.07.

Hypothesis seven (H7) states that the effect of Product Modularity on Internal Manufacturing Process Complexity is stronger under conditions of high environmental uncertainty, relative to low environmental uncertainty. This hypothesis is supported, as evidenced by two findings: (1) the coefficient on Product Modularity is not significant for the low uncertainty group at an alpha level of 0.05, but is positive and significant for the high group; (2) the point estimate for the Product Modularity coefficient for the high uncertainty group (0.154) is not contained within the 95% confidence interval of the Product Modularity coefficient for the low uncertainty group (-0.066 to 0.125). Both of these findings suggest that the relationship between Product Modularity and Internal Manufacturing Process Complexity is stronger under conditions of high environmental uncertainty.

Hypothesis eight (H8) states that the effect of Product Modularity on the complexity of organizational design and coordination is stronger under conditions of high environmental uncertainty, relative to low environmental uncertainty. This hypothesis was not supported. The coefficient on Product Modularity was nonsignificant in both the low and high uncertainty groups.

Hypothesis nine (H9) states that the effect of Product Modularity on Supply Base Complexity is stronger under conditions of high environmental uncertainty, relative to low environmental uncertainty. This hypothesis received partial support. In the low uncertainty group, the coefficient on Product Modularity was not significantly different from zero at the 0.05 alpha level, whereas in the high uncertainty group, the coefficient was positive and significantly different from zero. This is an indication that the relationship between Product Modularity and Supply Base Complexity is stronger for the high environmental uncertainty group. However, the point estimate for the Product Modularity coefficient for the high uncertainty group (0.137) falls within the 95% confidence interval of the Product Modularity coefficient for the low uncertainty group (-0.026 to 0.171). This result indicates that the equality of the two coefficients cannot be ruled out statistically.

6.5.0 Chapter Summary

In this chapter, discussions of preliminary analysis procedures and the method of analysis for hypothesis testing, Seemingly Unrelated Regression (SUR), were provided. Tests of twelve hypotheses were performed and a number of key findings were observed. First, Product Modularity has a positive and statistically significant influence on Supply Base Complexity. This result was present in the entire sample (n=88), as well as for the "open system" group (n=34), and the high environmental uncertainty group (n=39). Product Modularity was also found to have a positive and statistically significant effect on Internal Manufacturing Process Complexity. This result was evident in the "open system" group (n=34) and the high environmental uncertainty group (n=39). Product Modularity, however, was not found to have a statistically significant effect on the complexity of organizational design and coordination for any context examined in this study. A summary of the hypotheses tested and their results are provided in Table 6.7 below.

Table 6.7: Summary of Hypothesis Testing

	Statement of Hypothesis	**Result**
H1	*Product modularity influences the complexity of internal manufacturing processes.*	Not supported
H2	*Product modularity influences the complexity of organizational design and coordination.*	Not supported
H3	*Product modularity influences the complexity of a firm's supply base.*	Supported
H4a	*In closed systems, product modularity is positively associated with the complexity of internal manufacturing processes.*	Not supported
H5a	*In closed systems, product modularity is positively associated with the complexity of organizational design and coordination.*	Not supported
H6a	*In closed systems, product modularity is positively associated with the complexity of firms' supply bases.*	Not supported
H4b	*In open systems, product modularity is negatively associated with the complexity of internal manufacturing processes.*	Not supported
H5b	*In open systems, product modularity is negatively associated with the complexity of organizational design and coordination.*	Not supported
H6b	*In open systems, product modularity is negatively associated with the complexity of firms' supply bases.*	Not supported
H7	*The effect of product modularity on internal manufacturing process complexity is stronger under conditions of high environmental uncertainty.*	Supported
H8	*The effect of product modularity on organizational complexity is stronger under conditions of high environmental uncertainty.*	Not supported
H9	*The effect of product modularity on supply base complexity is stronger under conditions of high environmental uncertainty.*	Partially supported

7.0.0 Discussion

The primary research questions posed in this study investigated whether employing modularity at the product level has an impact on the complexity of supporting production systems, and if so, under what conditions does this result hold. The investigation of these questions involved breaking the production system down into three components: 1) the internal manufacturing process; 2) the organization (firm or SBU); and 3) the supply base. For each of these organizational levels, complexity was operationalized and then measured using perceptual scales. Operationalization and measurement of product modularity was conducted in similar fashion. These constructs were then used in the testing of twelve (12) hypotheses that address the primary research questions from a systems perspective. The results of measurement analysis and hypothesis testing are discussed in this chapter, as well as the limitations of the study and directions for future research.

7.1.0 Measurement Outcomes

Multi-dimensional measurement was attempted for each of the study constructs: Product Modularity, Manufacturing Process Complexity, Organizational Complexity, and Supply Base Complexity. For each of concept, constituent dimensions were derived from the extant literature on modularity and complexity. For modularity, three dimensions were proposed: 1) functional binding, 2) interface standardization, and 3) decomposability. For complexity, three dimensions were also studied: 1) number of elements, 2) heterogeneity of elements, and 3) interdependence of elements.

Each of the dimensions of the study's key constructs was evaluated for the fitness of its measurement properties. All constructs exhibited sound measurement properties according to the Nunnally (1978) criteria.

The results of measurement analysis suggest that manufacturing process complexity is driven primarily by the number of internal manufacturing processes employed to produce an organization's primary products. When considering a typology of manufacturing processes (i.e., project, batch, job shop, continuous, and assembly-line), for each type, the addition of a new process element requires an extra level of coordination in order to produce a finished product. This coordination may not be trivial, as in many cases it requires the establishment of new exchange protocols, the consideration of processing times, and the introduction of new quality checkpoints. It can be reasoned that this increased coordination effort stemming from an increase in the number of processes results in higher perceived complexity.

The interdependence and heterogeneity of the manufacturing process were not found to be significantly associated with its complexity. Heterogeneity may have little meaning in this context because processes are typically grouped by similar or complementary operations; hence by their very nature they are different from other processes. *How* different they are may have no effect on coordination required to produce the finished good. Regarding interdependence, the processes required to produce a finished good are necessarily dependent, however the level of dependence may depend on the type of process employed, with continuous and line flow processes tending toward higher dependence, and project, batch and job shop processes tending toward lower dependence. Because process interdependence may affect the level of complexity in different ways based on the type of process employed, its specific effect could be masked in the aggregate sample analyzed in this study.

From an organizational standpoint, both the number of organizational elements and the heterogeneity of organizational elements were found to significantly contribute to organizational complexity, while the interdependence of organizational elements showed no significant association with complexity. These results suggest that the larger and more dispersed an organization, and the more it employs dissimilar business systems, the more complex it is – a fairly intuitive finding. Less intuitive, however, is the absence of a relationship between organizational complexity and organizational interdependence. It may be that while interdependence increases the structural complexity of an organization, coordination is simplified due to better information flow. Consider the case of a matrix structure, a highly interdependent organizational design: the vertical (project team) and horizontal (functional group) assignment of human resources creates a more intricate organizational structure, but the bilateral communication that results could simplify coordination due to higher potential for shared knowledge. These offsetting effects could be responsible for the absence of a significant relationship between organizational interdependence and organizational complexity in this study.

Supply base complexity was shown to be influenced by both supply base heterogeneity and supply base interdependence; however, the relationship with supply base interdependence was negative. With regard to heterogeneity, the necessity of managing relationships with suppliers in different ways due to differences in size, location, and industry may serve to increase the amount of effort required for effective coordination. This is especially salient in situations where these differences create imbalance in the power distribution between buyer and suppliers, causing posturing and poor information flow to create a more adversarial and complex procurement environment (Kraljic, 1983, Benton and Maloni, 2005). The negative relationship between supply base interdependence and supply base complexity suggests that increased interdependence with suppliers results in decreased supply base complexity. This is likely owed to a recent increase in supplier integration initiatives, and firms' consolidation of supply requirements with partner organizations. This approach not only simplifies supply management through reduction in supplier count, but also the increased transparency and information flow allows for improved coordination and cost performance (Lee et al. 1997).

Surprisingly, the number of suppliers had no significant influence on supply base complexity. It could be that supply management organizations largely employ standard systems for managing suppliers, and increases in the number of suppliers pose no additional coordination burden, provided that the characteristics of transaction are not unique.

Overall, it was shown that the theoretically derived dimensions of Number, Heterogeneity, and Interdependence all have an influence on complexity. However, both the presence and the magnitude of these influences vary by level of analysis. This finding has important implications from both theoretical and practical perspectives. Complexity theory implies that the simultaneous presence of these three dimensions gives rise to complexity; however, it has been demonstrated here that the composition of the complexity construct is dependent upon the type of complexity being evaluated. In fact, in no case observed were all three dimensions significantly related to the construct. As such, it should be noted that direct perceptual measures of complexity are preferable to indirect measures due to the contingent nature of this construct. Measurement of complexity as a composite of its constituent dimensions may result in the inclusion of items that serve only to increase measurement error. In addition, direct perceptual measurement offers a more parsimonious approach, as fewer items are required to achieve sound measurement properties.

Product modularity, on the other hand, was shown to be reliably measured as a composite of its theoretically derived dimensions, although its dimensions were not found to be independent of one another. Each dimension exhibited very strong correlation with its counterparts, which is an indication of the unity of the modularity construct. These results supports recent literature that suggest that modularity is a multi-dimensional concept (Schilling, 2000; Salvador, 2007), but also illustrate that its measurement need not establish each dimension as a distinct measurable element. Rather measurement may proceed by merely ensuring that each dimension is adequately represented in the modularity scale.

7.2.0 Results and Conclusions of Hypothesis Testing

Product modularity was found to be positively associated with the complexity of internal manufacturing processes under conditions of high outsourcing and high environmental uncertainty, and the relationship was nearly significant (p=0.055) in the general sample. A quick tour through a modern automotive assembly plant is all that is required to understand this finding. In this setting, it is not uncommon for assemblers to receive cockpits, seating systems, headliners, and even drivetrains as pre-assembled modules. The assembly of these modules into a finished vehicle is a symphony of highly coordinated deliveries, automated part storage and retrieval, and integrated component assembly, inspection, and certification. The configuration of these plants represents a modern spin on the Henry Ford assembly line, where standardized components have been replaced by modules with standardized interfaces. The tremendous number of product configurations made possible through the receipt of different flavors of each module requires that the assembly process itself has enough sophistication (or complexity) to maintain high volume throughput, while simultaneously providing the level of customization demanded by consumers. The necessary level of process sophistication increases with the number of assemblies received from external suppliers and the variability in consumer demand for different product configurations.

Product modularity was also found to be positively associated with the complexity of the supply base in general, as well as under conditions of high outsourcing and high environmental uncertainty. This result is best illustrated through the example of the Boeing 787 Dreamliner, a highly modularized and extensively outsourced aircraft design. Problems with the integration of modules and coordination difficulties with suppliers for component design and delivery plagued this product from the start, and resulted in a launch delay of over two years. As a result, Boeing has vowed to reign in much of the design for the next generation of this product in efforts to reduce the complexity in its supply chain (Sanders, 2009). This result was also typical of software, telecommunications and consumer electronics firms evaluated in a study by Staudenmeyer et al. (2005), where modularization and concurrent design of products across partnering firms resulted in increases in supply base complexity, as well as difficulty in managing the design and release of new products.

Product modularity was not, however, found to have an association with the complexity of organizational design and coordination for any context examined. Through conversations with focal firm participants, it became clear that the organizational transformation that follows product modularization quite often represents a final phase of transition. It was observed that only after a firm had experience in designing and launching modular products, and had decided to adopt modularization as its primary product design strategy, that it began to realize how its organization could best be restructured to support this strategy. Because modular design is still relatively new to many of the industries under study here, it is possible that many of the firms observed have yet to reach this critical stage of development.

As evidenced by these findings, the open and closed systems framework may not accurately characterize the relationship between modularity and complexity in production systems. It was hypothesized that in an open system setting that product modularity would trigger a decrease in complexity, and the converse was hypothesized for closed systems. It was discovered, however, that in all cases where product modularity was significantly related to production system complexity, the result was an increase in complexity. One reason for this result may be that the proxy used to represent system openness (degree of outsourcing) was not effective in segmenting the sample according to the true characteristics of open and closed systems. However, the degree of outsourcing is a good indicator of the extent of control an organization has over its product design, which is consistent with the arguments presented to support open and closed systems hypotheses in section 3.2.2. Another reason could be that the extent of use of modularity in closed or low-outsourcing systems observed in the study was systematically low, hence lower levels of modularity application and decreased variability preclude the ability to detect a relationship with complexity. However, a comparison of the means and standard deviations of modularity scale values between low and high outsourcing groups indicates that both the extent of modularity use and its corresponding variability are not statistically different across groups at a 5% significance level. It is likely then that another theoretical perspective offers a better explanation of the phenomenon under study than open and closed systems.

As an alternative explanation, a *Law of Conservation of Complexity* is proposed. Similar to the *Law of Conservation of Energy* which states that the energy in an isolated system cannot be destroyed, this proposition suggests that complexity in a production system is not eliminated – like energy, it merely changes form. As such, the application of modular product architecture may reduce complexity at the product level by lowering part count and minimizing interdependencies (Baldwin and Clark, 2000), while increasing complexity in other parts of the production system. The findings herein support this notion of a *complexity shift*, as all significant relationships observed indicate an increase in other forms of complexity (i.e., manufacturing process complexity and supply base complexity) associated with product modularity.

7.3.0 Contributions to Business Theory and Practice

This study contributes to the Operations and Supply Chain Management (OSM) body of knowledge and business practice in a number of ways. First, it provides empirically validated perceptual measures of Product Modularity, Manufacturing Process Complexity, Organizational Complexity and Supply Chain Complexity. Measures of these concepts have been called for by Salvador (2007) and Choi and Krause (2006). Product modularity was measured using a six-item scale, with items representing each of its three theoretically derived dimensions: functional binding, interface standardization, and decomposability. Complexity measures were each composed of three items that tap the construct directly by asking questions about structural intricacy and difficulties in coordination. These scales can be utilized, as well as further refined and validated, in future studies observing modularity and complexity in an OSM context.

Next, it was found that complexity is composed of a different mix of its theoretically derived dimensions, contingent upon the type of complexity under study. Organizational complexity was found to be driven by the number and heterogeneity of organizational elements; supply base complexity was shown to be positively influenced by supplier heterogeneity and negatively influenced by the interdependence between organizations and their suppliers; and manufacturing process complexity was found to be a function of only the number of manufacturing processes employed in the creation of firms' primary products.

This finding is important in that it highlights the areas which most impact complexity at different organizational levels, thereby allowing for more focused efforts to be applied toward its reduction.

The study examined the impact of a product-level characteristic on the characteristics of its supporting production system. This was done by employing a multi-level research design, whereby information was collected about both the technical and managerial aspects of an organization. Very few studies in Operations and Supply Management have employed this type of design, even though it is crucial to understanding the broader impacts of strategically-motivated decisions.

The findings demonstrate that the Open / Closed Systems framework does not accurately characterize the relationship between modularity and complexity in production systems. It was hypothesized that in an open system setting that product modularity would trigger a decrease in complexity, and the converse was hypothesized for closed systems. It was discovered, however, that in all cases where product modularity was significantly related to production system complexity, the result was an increase in complexity. A new framework, the Law of Conservation of Complexity, was proposed as an alternative explanation for the behavior exhibited. Perhaps this framework can be applied to further examination of complexity behavior in other organizational systems.

Finally, the study provides managers with deeper insight regarding the consequences of pursuing modularity as a design strategy. Results indicate that product modularity is associated with increases in manufacturing process complexity and supply base complexity. This is a key finding, as most studies on the subject focus on the performance benefits of employing modularity, such as improved flexibility (Worren et. al, 2002) and faster product development cycles (Fine, 2000), without discussing the potential challenges that may arise as a result of its application. The findings indicate that there is a tradeoff to pursuing a modular product design strategy. Although modularity may serve to simplify product designs, enabling a quicker turn around on product updates, it may create stress in other parts of the manufacturing and product delivery system. In cases where complexity is more cost-effectively managed on the support side of manufacturing, this tradeoff may be worthwhile, as in the case of highly complex products. Conversely, this may not be the case for products with simpler product designs, as the cost of managing changes at the product level may be low in comparison to the costs of managing complexity in manufacturing processes and supply chains. This information should help managers make more informed decisions regarding the choice to pursue product modularity, and better prepare them for the likely impact on their production support systems.

7.4.0 Limitations and Directions for Future Study

The use of single respondents could have resulted in common method bias. While this study did not rely solely on single respondents, the percentage of paried observations from two individuals within an organization (29%) was fairly low in comparison to observations received from a single respondent (71%). This approach, in conjunction with the randomization of questions during survey implementation and the varying of the sentence structure of questions, both recommended by Podsakoff et al. (2003), was employed to reduce the potential for common method bias. As a test to determine if the use of common methods skewed the results of the study, the parameter estimates of the SUR model fit to the data for single respondents were compared against those produced by the data from dual respondents. The was no statistical difference in the regression coefficients for the main study variables between the two groups, indicating that common method bias does not pose a serious threat to the validity of the study. However, future studies of this nature should strive to employ the multiple-respondent approach to a greater extent.

The level of agreement between respondents from the same organization, as evaluated using the Intraclass Correlation Coefficient (ICC), was slightly lower than recommended. Boyer and Verma (2000) suggest 0.60 as a minimum value for the average ICC across questions asked of multiple respondents from a single organization in operations research. The average ICC across four questions asked of managers and technical personnel in this study was 0.58. The was likely due to the fact that respondents from the same organization were recruited for participation based on differences in their skill sets and knowledge bases. It is unlikely that individuals in the technical sphere of an organization share the same perspectives of the business as those in management, therefore greater differences were likely to be detected here than in situations where respondents of similar function are recruited to respond to the same questions. Future studies of this type should place greater emphasis on identifying those questions which have a high likelihood of being perceived similarly by individuals operating at different levels of the organization in order to provide a stronger test of agreement.

Although the sample sizes for both the technical (n=169) and managerial (n=188) samples were comparable to most large scale studies performed in Operations and Supply Management, the number of merged observations (n=94) was somewhat lower than desired. As a result, the study could not employ the purely multivariate analysis methods for testing hypotheses that are typical of this kind of research. However, the methods selected were carefully chosen to minimize the potential shortcomings of small sample analysis.

In addition, the study employed two-item measures for manufacturing process heterogeneity and supply base heterogeneity. Studies intending to test hypotheses including these concepts should employ more items for measurement to ensure that these constructs exhibit sound psychometric properties.

This study raises many new questions concerning both modularity and complexity, as they relate production systems, which were not addressed with analyses performed for this study. The findings of measurement analysis revealed that a different mix of the theoretically derived dimensions of complexity were significantly associated with various types of production system complexity. It was reasoned that different types of processes and organizational designs could be responsible for the differences in these findings. Future studies could examine this phenomenon by explicitly accounting for these differences in process and organizational composition. Also, interdependence with suppliers was found to be negatively related to supply base complexity. The diffusion of the principles of Supply Chain Management, and in particular the increasing deployment of Supplier Integration as a strategic initiative, was offered as a possible explanation for this result. Follow up studies could perform an explicit test of the relationship between supplier integration and supply base complexity.

Finally, the role of time was introduced as a possible explanation for the failure to detect a relationship between product modularity and organizational complexity. Future studies should employ a longitudinal design in order to effectively examine this relationship. Longitudinal analyses would also be well suited for testing the *Law of Conservation of Complexity* proposition. This approach would allow researchers to observe the mechanism by which product modularity facilitates the transformation of production support systems.

APPENDICES

APPENDIX A. Research Questionnaire

Table A.1 - Technical Section

	Please indicate the extent to which you agree or disagree with the following questions regarding the characteristics of your primary products. **{Please answer anywhere from 1=Strongly Disagree to 7=Strongly Agree}**
PD-FB1	*For our products, we can make changes in components without changing other components.*
PD-FB2	*For our products, functions can be directly added or deleted by adding or removing components.*
PD-FB3	*Our product design is such that a given product function is performed by a single product component.*
PD-FB4	*Our products have interchangeable features and options.*
PD-IS1	*Our product components have standardized interfaces.*
PD-IS2	*The interfaces of our product components are designed to accept a variety of components.*
PD-IS3	*Our product components are able to accept a wide range of complements (such as modules or peripherals).*
PD-IS4	*Each component interface is unique. (reversed item)*
PD-DC1	*Our products can be decomposed into separate modules.*
PD-DC2	*Our products are designed to be easily disassembled and reassembled.*
PD-DC3	*Our products are designed to be easily reconfigured.*
	Please indicate the extent to which you agree or disagree with the following questions regarding the characteristics of your production processes. **{Please answer anywhere from 1=Strongly Disagree to 7=Strongly Agree}**
PC-INT1	*Our production processes are broken down into sub-processes that can operate independently. (reversed item)*
PC-INT2	*Sub-processes can be added to or removed from our production processes without changing other sub-processes. (reversed item)*
PC-INT3	*Our production processes are designed so that sub-processes can be added or removed without significant disruptions/changes to other sub-processes. (reversed item)*
PC-HTR1	*The products we make have similar processing and assembly requirements. (reversed item)*
PC-HTR2	*Only minor equipment modifications are required to produce different products. (reversed item)*
PC-HTR3	*We are frequently forced to make changes in our manufacturing processes to satisfy differing customer requirements.*

Table A.1 (cont.)

PD-MOD1	*Our products are designed to enable the swapping of components.*
PC-CMP1	*Our production system is very sophisticated in terms of its operating characteristics.*
PC-CMP2	*Our production system is very complex.*
PC-CMP3	*Our production system is very sophisticated in terms of structure/layout.*
	Please answer the following question regarding the nature of your operation by selecting from the options provided below.
	Number of internal manufacturing processes: *(1) – 1* *(2) – 2 or 3* *(3) – 4 or 5* *(4) – 6 or 7* *(5) – 8 or 9* *(6) – 10 or 11* *(7) – 12 or more*

Table A.2 - Managerial Section

	Please indicate the extent to which you agree or disagree with the following questions regarding the characteristics of your firm or SBU. **{Please answer anywhere from 1=Strongly Disagree to 7=Strongly Agree}**
OG-HTR1	*Sub-units in our firm/SBU are subject to the same policies (ex.: quality standards, compensation, absenteeism, etc.). (reversed item)*
OG-HTR2	*Sub-units in our firm/SBU employ similar or compatible business practices. (reversed item)*
OG-HTR3	*Sub-units in our firm/SBU have similar or compatible information systems/technologies. (reversed item)*
OG-HTR4	*Sub-units in our firm/SBU use common mechanisms for coordinating work. (reversed item)*
OG-HTR5	*The organizational structures of sub-units in our firm/SBU are similar. (reversed item)*
OG-INT1	*Project teams are self-directed. (reversed item)*
OG-INT2	*Project teams operate autonomously. (reversed item)*
OG-INT3	*Project teams operate independently from other organizational entities. (reversed item)*
OG-INT4	*Project teams are free to develop links with other teams and/or internal units in our firm/SBU. (reversed item)*

Table A.2 (cont.)

OG-INT5	*Project teams are free to develop links with external units such as suppliers, customers, etc. (reversed item)*
OG-CMP1	*Our firm/SBU has a very complex organizational structure.*
OG-CMP2	*Our firm/SBU is organized in a straight-forward, uncomplicated way. (reversed item)*
OG-CMP3	*Coordinating work between sub-units in our firm/SBU is difficult.*
	Please indicate the extent to which you agree or disagree with the following questions regarding the characteristics of your supply chain. **{Please answer anywhere from 1=Strongly Disagree to 7=Strongly Agree}**
SB-INT1	*We have frequent face-to-face communication with key suppliers.*
SB-INT2	*For a given supplier, there are multiple points of contact between our organization and the supplier's.*
SB-INT3	*We have long-term relationships with our suppliers.*
SB-INT4	*We have strong ties to our suppliers.*
SB-HTR1	*Our suppliers are diverse in terms of size, location, and products supplied.*
SB-HTR2	*Effective management of procurement requires taking different approaches with different suppliers.*
SB-CMP1	*Coordinating procurement and manufacturing operations is problematic for our firm/SBU.*
SB-CMP2	*The structure of our supply chain is difficult to describe or illustrate.*
SB-CMP3	*Our supply chain is a very complex network.*
	Please complete the following statements regarding the market for your primary product line by selecting from the responses provided below.
EN-UNC1	*Sales forecasts for our primary products are likely to be: (very inaccurate…very accurate)*
EN-UNC2	*Predicting the actions of our competitors is: (very easy…very difficult)*
EN-UNC3	*Predicting consumer tastes in our market(s) is: (very easy…very difficult)*
EN-UNC4	*Monitoring market trends for our primary products is: (very easy…very difficult)*
EN-UNC5	*Predicting demand for our primary product line is: (very easy…very difficult)*

Table A.2 (cont.)

	Please provide the following demographic data for your firm or SBU by selecting from the options provided below.
	Number of worldwide locations managed by your firm or SBU: *(1) – 1* *(2) – 2 to 10* *(3) – 11 to 20* *(4) – 21 to 30* *(5) – 31 to 40* *(6) – 41 to 50* *(7) – more than 50*
	Number of organizational levels in your firm or SBU – from the lowest level employee to the top management position: *(1) – 1* *(2) – 2 or 3* *(3) – 4 or 5* *(4) – 6 or 7* *(5) – 8 or 9* *(6) – 10 or 11* *(7) – 12 or more*
	Number of operating divisions: *(1) – 1* *(2) – 2 or 3* *(3) – 4 or 5* *(4) – 6 or 7* *(5) – 8 or 9* *(6) – 10 or 11* *(7) – 12 or more*
	Number of suppliers used by your firm or SBU: *(1) – less than 10* *(2) – 10 to 50* *(3) – 51 to 100* *(4) – 101 to 500* *(5) – 501 to 1000* *(6) – 1001 to 5000* *(7) – more than 5000*
	Please provide the following demographic data for your firm or SBU: ***Approximate values are acceptable***
	Number of employees
	Total sales

APPENDIX B. Sample Invitation and Follow-up Letters

Exhibit B.1 – Invitation Letter

From: Delvon B. Parker [msubcrt@bus.msu.edu]
Sent: Tuesday, April 14, 2009
Subject: Modularity Research with Michigan State University

Dear <recipients full name>,

I am writing you today to ask for your participation in a study on the concept of *Modularity* that I am conducting with the Department of Supply Chain Management at Michigan State University's Eli Broad College of Business. I am polling manufacturing professionals, such as yourself, in the electronics and transportation industries to get an idea of how extensive modularity is applied in US-based firms.

Participation in the study is completely voluntary and involves only the completion of a 25-minute online survey. Your insights are critical in helping us to evaluate modularity's ability to impact key performance measures, reduce operational complexity, and accelerate innovation. All participants will receive a summary report of the study's findings.

The survey, which is split into two parts (technical and managerial), asks a series of very general questions about your products, the manufacturing processes that produce them, your organization and its supply base. Most of the questions are agree/disagree type questions that address characteristics of your products, processes and organization in a very indirect way.

In order to access the survey, please follow the link for the section that is most relevant to your current role, and enter the password when prompted. The links for each section, and the password (which works for either section) are provided below:

Survey Link: Managerial Section
Survey Link: Technical Section

Password: modres2009

Be assured that information collected for this study will be kept confidential to the extent allowable by local, state and federal law. Completed surveys will be stored securely and will be available only to members of the research team. No reference will be made in any oral or written report that would link you individually, or your company, to the study.

Thanks in advance for your interest and participation in the study. If you have any questions or concerns, you can reach me by phone during normal business hours at (517) 432-6455, or at any time by e-mail at msubcrt@bus.msu.edu.

Thanks again,

Delvon B. Parker
Doctoral Candidate, Operations Management
Eli Broad College of Business
Michigan State University

Exhibit B.2 – Follow-up Letter #1

From: Delvon B. Parker [msubcrt@bus.msu.edu]
Sent: Tuesday, April 21, 2009
Subject: Follow up request for participation in modularity research with MSU

Dear <recipients full name>,

I hope you received my prior invitation to participate in research on *Modularity* with Michigan State University. Interest in this concept has grown steadily over the past decade, and many firms have begun adopting modularity as their principal product design strategy. However, the impact of modularity on operational performance is still somewhat unclear. Your insights will help us gain a better understanding of how exactly modularity affects various aspects of performance (such as costs, quality, innovation, etc.). Even if you are not currently employing modularity, your responses are extremely valuable for comparison purposes. Results will be made available to all study participants.

Over 120 firms in electronics, transportation and closely related industries have already participated, and I hope that you will strongly consider participation as well. The two-part survey (technical and managerial) contains very general questions about your products and manufacturing processes, your organization and its supply base. Nearly all of the questions are of the agree/disagree type, and the survey takes only 25 minutes to complete. You may even elect to participate anonymously.

In order to access the survey, please follow the link for the section that is most relevant to your current role, and enter the password when prompted. The links for each section, and the password (which works for either section) are provided below:

Survey Link: **Managerial Section**
Survey Link: **Technical Section**

Password: modres2009

Please do not hesitate to contact me if you have any questions regarding any aspect of the study. I can be reached by phone Monday through Friday, 8:00 a.m. to 5:00 p.m. EST at (517) 432-6455, or at any time by e-mail at msubcrt@bus.msu.edu.

Thank you very much for further considering participation,

Delvon B. Parker
Doctoral Candidate, Operations Management
Eli Broad College of Business
Michigan State University
Phone: (517) 432-6455

Exhibit B.3 – Follow-up Letter #2

From: Delvon B. Parker [msubcrt@bus.msu.edu]
Sent: Monday, April 27, 2009
Subject: Thanks for your patience and participation

Dear <recipients full name>,

Thank you very much for your patience in receiving my prior e-mails. Michigan State University relies strongly on industry professionals like you to provide a much needed real-world perspective to our research and educational efforts, which is why I have contacted you so frequently. Without your support, the relevance of the work we do with industry, and in the classroom, suffers tremendously.

If you have already participated in the modularity research project by completing our online survey, we extend you our most sincere thanks. You will receive a report on the major findings of the research as soon as our analysis is complete.

If you have not yet had the opportunity to complete the survey, I would like to take this final opportunity to ask for your participation in this very important research. The survey will close on Friday, May 1, 2009 at 5:00 p.m. (EST). Twenty-five minutes of your time will go a long way toward helping us learn more about modularity applications and their true value to the manufacturing sector.

To access the survey, please follow the link for the section that is most relevant to your current role, and enter the password when prompted.

Survey Link: **Managerial Section**
Survey Link: **Technical Section**

Password: modres2009

Thanks again for your interest, your patience, and your participation. Your response will help shape education on modularity, as well as its future application.

Sincerely,

Delvon B. Parker
Doctoral Candidate, Operations Management
Eli Broad College of Business
Michigan State University
Phone: (517) 432-6455
E-mail: msubcrt@bus.msu.edu

APPENDIX C. Sample Breakdown by Various Categories

By Contact Information Source	No. in sample (% of total)
Institute of Industrial Engineers (IIE)	97 (33%)
Heavy Equipment Manufacturer and Tier 1 Suppliers	72 (25%)
Society of Manufacturing Engineers (SME)	65 (22%)
Household Appliance Manufacturer and Tier 1 Suppliers	29 (10%)
Department of Marketing and Supply Chain Management (MSU) Mailing List	16 (6%)
Aircraft Engine Manufacturer and Tier 1 Suppliers	11 (4%)
Total Responses	290
By Industry (Industry Classification Code)	
Transportation Equipment Manufacturing (NAICS: 336)	83 (28.6%)
Fabricated Metal Product Manufacturing (NAICS: 332)	39 (13.4%)
Electrical Equipment, Appliance, and Component Manufacturing (NAICS: 335)	38 (13.1%)
Miscellaneous Manufacturing (NAICS: 339)	38 (13.1%)
Primary Metal Manufacturing (NAICS: 331)	18 (6.2%)
Machinery Manufacturing (NAICS: 333)	17 (5.9%)
Computer and Electronic Product Manufacturing (NAICS: 334)	16 (5.5%)
Plastics and Rubber Products Manufacturing (NAICS: 326)	9 (3.1%)
Printing and Related Support Activities (NAICS: 323)	5 (1.7%)
Food Manufacturing (NAICS: 311)	4 (1.4%)
Nonmetallic Mineral Product Manufacturing (NAICS: 327)	3 (1.0%)
Wood Product Manufacturing (NAICS: 321)	2 (0.7%)
Petroleum and Coal Products Manufacturing (NAICS: 324)	2 (0.7%)
Furniture and Related Product Manufacturing (NAICS: 337)	2 (0.7%)
Textile Product Mills (NAICS: 314)	1 (0.3%)
Leather and Allied Product Manufacturing (NAICS: 316)	1 (0.3%)
Chemical Manufacturing (NAICS: 325)	1 (0.3%)
Other (Non-manufacturing industries)	11 (3.8%)
Total Responses	290
By Questionnaire Type	
Managerial	188 (52.7%)
Technical	169 (47.3%)
Total Questionnaires	357*
By Paired/Non-Paired Cases	
Paired (Both Managerial and Technical Responses per SBU)	94 (35.7%)
Non-Paired (Either Managerial or Technical Response Only per SBU)	169 (64.3%)
Total Cases	263^

**Sixty-seven (67) individuals completed both the Managerial and Technical questionnaire. 290+67=357*

^Twenty-seven (27) cases had two responses per SBU, one technical and one managerial. 290-27=263

APPENDIX D. Technical CFA – All Product and Process-Related Constructs

	Scale (Reliability) / *Question*	Std. Loading
	Product Modularity (0.907)	
PD-MOD1	*Our products are designed to enable the swapping of components.*	0.720**
PD-FB2	*For our products, functions can be directly added or deleted by adding or removing components.*	0.707**
PD-FB4	*Our products have interchangeable features and options.*	0.767**
PD-IS2	*The interfaces of our product components are designed to accept a variety of components.*	0.846**
PD-IS3	*Our product components are able to accept a wide range of complements (such as modules or peripherals).*	0.820**
PD-DC3	*Our products are designed to be easily reconfigured.*	0.765**
	Process Interdependence (0.836)	
PC-INT1	*Our production processes are broken down into sub-processes that can operate independently. (reversed item)*	0.660**
PC-INT2	*Sub-processes can be added to or removed from our production processes without changing other sub-processes. (reversed item)*	0.875**
PC-INT3	*Our production processes are designed so that sub-processes can be added or removed without significant disruptions/changes to other sub-processes. (reversed item)*	0.855**
	Process Heterogeneity (2-item correlation=0.387)	
PC-HTR1	*The products we make have similar processing and assembly requirements. (reversed item)*	0.533**
PC-HTR2	*Only minor equipment modifications are required to produce different products. (reversed item)*	0.720**
	Process Complexity (0.893)	
PC-CMP1	*Our production system is very sophisticated in terms of its operating characteristics.*	0.809**
PC-CMP2	*Our production system is very complex.*	0.882**
PC-CMP3	*Our production system is very sophisticated in terms of structure/layout.*	0.884**
	Fit Statistics: Chi-Square=164.3, df=71; CFI=0.924; GFI=0.874; SRMR=0.0731; RMSEA=0.089	**p<0.05

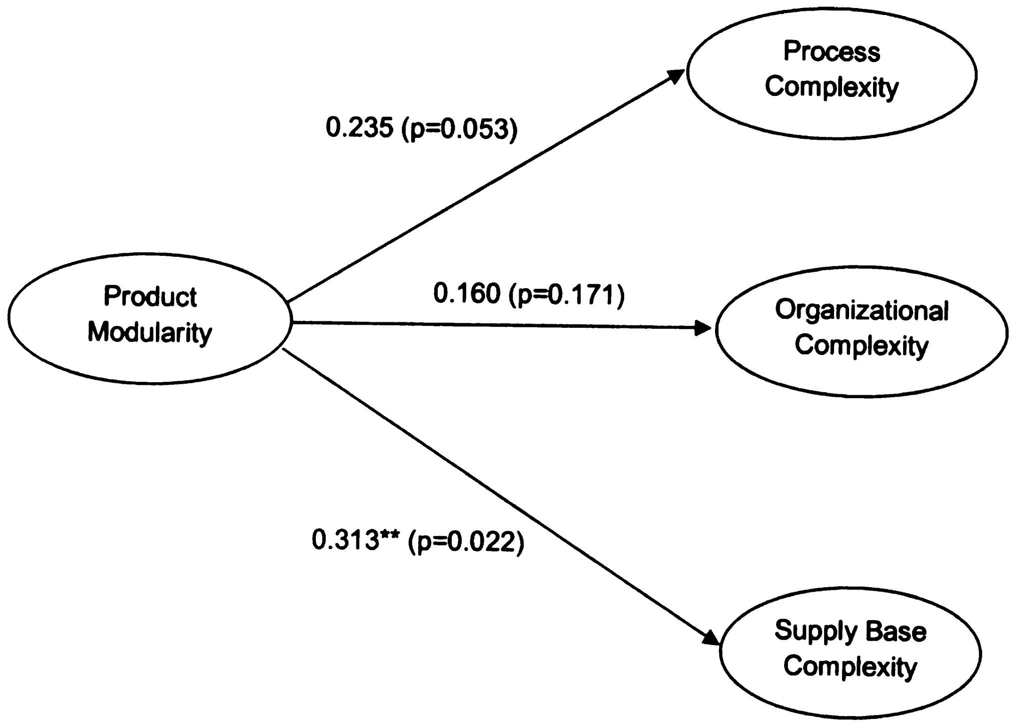
APPENDIX E. Managerial CFA – All Organization and Supply Base-Related Constructs

	Scale (Reliability) / *Question*	Std. Loading
	Organizational Heterogeneity (0.807)	
OG-HTR1	*Sub-units in our firm/SBU are subject to the same policies (ex.: quality standards, compensation, absenteeism, etc.). (reversed item)*	0.739**
OG-HTR2	*Sub-units in our firm/SBU employ similar or compatible business practices. (reversed item)*	0.779**
OG-HTR3	*Sub-units in our firm/SBU have similar or compatible information systems/technologies. (reversed item)*	0.682**
OG-HTR4	*Sub-units in our firm/SBU use common mechanisms for coordinating work. (reversed item)*	0.677**
	Organizational Interdependence (0.720)	
OG-INT1	*Project teams are self-directed. (reversed item)*	0.598**
OG-INT4	*Project teams are free to develop links with other teams and/or internal units in our firm/SBU. (reversed item)*	0.829**
OG-INT5	*Project teams are free to develop links with external units such as suppliers, customers, etc. (reversed item)*	0.635**
	Organizational Complexity (0.763)	
OG-CMP1	*Our firm/SBU has a very complex organizational structure.*	0.803**
OG-CMP2	*Our firm/SBU is organized in a straight-forward, uncomplicated way. (reversed item)*	0.763**
OG-CMP3	*Coordinating work between sub-units in our firm/SBU is difficult.*	0.627**
	Environmental Uncertainty (0.802)	
EN-UNC2	*Predicting the actions of our competitors is: (very easy...very difficult)*	0.631**
EN-UNC3	*Predicting consumer tastes in our market(s) is: (very easy...very difficult)*	0.801**
EN-UNC4	*Monitoring market trends for our primary products is: (very easy...very difficult)*	0.758**
EN-UNC5	*Predicting demand for our primary product line is: (very easy...very difficult)*	0.660**
	Supply Base Interdependence (0.753)	
SB-INT1	*We have frequent face-to-face communication with key suppliers.*	0.608**
SB-INT3	*We have long-term relationships with our suppliers.*	0.799**
SB-INT4	*We have strong ties to our suppliers.*	0.756**

Appendix E (cont.)

	Supply Base Heterogeneity (2-item correlation=0.362)	
SB-HTR1	*Our suppliers are diverse in terms of size, location, and products supplied.*	0.628**
SB-HTR2	*Effective management of procurement requires taking different approaches with different suppliers.*	0.577**
	Supply Base Complexity (0.672)	
SB-CMP1	*Coordinating procurement and manufacturing operations is problematic for our firm/SBU.*	0.636**
SB-CMP2	*The structure of our supply chain is difficult to describe or illustrate.*	0.677**
SB-CMP3	*Our supply chain is a very complex network.*	0.620**
	Fit Statistics: Chi-Square=365.3, df=188; CFI=0.876; GFI=0.854; SRMR=0.067; RMSEA=0.071	**p<0.05

APPENDIX F. SEM Analysis of Exploratory Model



Fit Statistics:

Chi-Square=194.9, df=87; CFI=0.835; GFI=0.788;
SRMR=0.132; RMSEA=0.119

*Notes: **p<0.05*

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