

Breaking Mirror for the Customers: The Demand-Side Contingencies of the Mirroring Hypothesis

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ABSTRACT

Much of the literature on modularity suggests that increased product modularity is associated with advantageous increases in organizational modularity, otherwise known as the mirroring hypothesis. However, there is growing contradictory evidence. This study proposes demand-side contingent factors that would reduce the extent of mirroring between product and organization. Specifically, it is proposed that firms adopting industry-standard modular architecture would “break the mirror” (i.e., remain relatively more integrated) if the target customers have high performance or reliability demands. Logit regression is employed to test the proposed hypotheses on the cross-sectional data collected from 173 computer systems integration firms (177 strategic business units). Results support the proposed demand-side contingent factors, i.e., an increase in target customers’ performance and reliability demand indeed reduces the extent of mirroring for systems integration firms in this industry.

Keywords: Modularity, Product architecture, Organizational structure, Mirroring hypothesis, Demand-side contingencies.

INTRODUCTION

Scholars across a wide range of disciplines advocate modularity as a solution to growing complexity in technology and organization (e.g., Baldwin & Clark, 1997, 2000; Conway, 1968; Pahl et al., 1996; Parnas, 1972; Sanchez & Mahoney, 1996; Schilling, 2000, 2002; Simon, 1962; Suh, 2005). Specifically, management scholars put forth the so-called “mirroring hypothesis,” which postulates that the structure of an organization and the architecture of the product it is developing would come to “mirror” each other (Colfer & Baldwin, 2016; Henderson & Clark, 1990; Sanchez & Mahoney, 1996). As

a result, many expect product modularity leads to various benefits associated with organizational modularity, such as reduced coordination costs (Padmanabhan & Raghunath, 2020; Raasch, 2011; Srikanth & Puranam, 2011), easier outsourcing or offshoring (Fontana & Prencipe, 2013; Rotaba & Beaudry, 2012; Sako, 2004), and increased organizational flexibility (Hoetker, 2006; Sanchez, 1995; Wang et al., 2004).

However, a growing ‘revisionist’ literature contends that the enthusiasm for modularity has gone too far (Ernst, 2005), and product architecture and organizational structure do not always mirror each other (Brusoni, 2005; Brusoni & Prencipe, 2001; Brusoni et al., 2001; Takeishi, 2002). To date, empirical evidence remains highly conflicted. Thus, many researchers have turned their attention to finding contingent factors to explain when the mirroring hypothesis would or would not hold (see Sorkun & Furlan, 2017). Studies over the past decade have identified numerous contingency factors, such as product complexity (Vickery et al., 2016), stability of product architecture (Cabigiosu & Camuffo, 2012; Furlan et al., 2014), and detailed knowledge about module interactions (Leo, 2020; Zirpoli & Becker, 2011). However, the majority of the research stream focuses solely on supply-side contingency factors and does not investigate whether there are unexplored contingency factors on the mirroring hypothesis on the demand side.

This empirical study explores demand-side contingencies on the mirroring relationship between product and organization to address this research gap. Specifically, this study examines mirroring in the context of systems integration firms that have adopted industry-standard modular architecture. Given the same product architecture and underpinning technologies, extant theories of mirroring would predict similar levels of organizational modularity among these firms. Instead, it is predicted that the extent of mirroring would be reduced for firms targeting customers with high demands for system performance, as well as firms targeting customers who would suffer great economic loss in the event of system failures, i.e., customers with high demands for system reliability.

This study tests these hypotheses with a distinctive empirical setting that allows variance in demand characteristics while holding product architecture constant. Thus, the observed variance in organizational modularity can be attributed to the contingent role of demand characteristics. The empirical results lend support to the hypothesized demand-side contingencies and also point to the need for more careful theoretical and empirical investigation to untangle the impacts of different demand-side factors on the mirroring relationship. The findings of this study contribute to the growing empirical evidence of contingencies on mirroring and help resolve parts of the debate on the organizational implications of modularity.

This paper proceeds as follows. The next section provides a brief review of the

literature on the mirroring hypothesis to set the stage for the theoretical development in the following section. The subsequent section discusses the empirical challenges to testing the mirroring hypothesis and how the adopted research design overcomes these challenges, followed by a description of the empirical method and a discussion of the findings. Finally, the paper discusses some limitations of the study and presents the conclusions.

LITERATURE REVIEW

Mechanisms of Mirroring

Research pioneered by Sanchez and Mahoney (1996) and Baldwin and Clark (2000) provides the seminal basis for the literature on the mirroring hypothesis. The core idea is that standardized component interfaces in a modular product architecture can provide a form of embedded coordination, thereby greatly reducing the need for overt organizational coordination mechanisms. According to Sanchez and Mahoney, modular component development processes “can be effectively coordinated simply by requiring that all developed components conform to the standardized component interface specifications” (1996, p. 65). Thus, interface standardization decouples component development processes so they can be carried out concurrently and autonomously (Sanchez, 1996). In other words, modular product designs enable modular organization designs with loosely coupled structures (Sanchez, 1995). Subsequently, interface standardization is considered synonymous with product modularity in much of the literature (Cabigiosu et al., 2013; Salvador, 2007; Yung & Tsai, 2016).

Another idea fundamental to the mirroring hypothesis is the principle of information hiding (Baldwin, 2007; Baldwin & Clark, 2000; Parnas, 1972), which stipulates that information about the inner workings of one modular component need not be shared with the development teams of other components (Hoetker, 2006). As a result, the amount of communication required to achieve coordination is reduced. In addition, information hiding also increases the ability to make changes to one modular component without affecting others (MacCormack et al., 2006). Thus, information hiding increases both organizational and product modularity (Colfer & Baldwin, 2016).

The Revisionist Literature

Numerous prior studies have supported the mirroring hypothesis (see Colfer & Baldwin, 2016). However, an increasing number of empirical studies (Cabigiosu et al., 2013; MacDuffie, 2013; Staudenmayer et al., 2005; Zirpoli & Becker, 2011) find that firms adopting modular product designs through interface standardization still face coordination issues. For example, Staudenmayer et al. (2005) found that despite ex-ante interface standardization, interdependencies across component development teams

continue to emerge throughout product development. These findings suggest that there are circumstances in which interface standardization cannot fully decouple component development processes or eliminate the need for overt organizational coordination. Accordingly, many scholars conclude that there is no one-to-one mapping between the product and organizational architectures (Brusoni, 2005; Brusoni & Prencipe, 2001; Brusoni et al., 2001). Hence, finding contingent factors might be more important than debating whether the mirroring hypothesis holds or not (Furlan et al., 2014).

Contingent Factors

Researchers have since identified a long list of contingent factors that influence the extent of mirroring between product and organization (Cabigiosu & Camuffo, 2012; Furlan et al., 2014; Leo, 2020; Sorkun & Furlan, 2017; Vickery et al., 2016; Zirpoli & Becker, 2011). Notably, Sorkun and Furlan (2017) carried out a citation network analysis on the extant empirical studies and found six clusters of contingent factors: (1) component technological change and diversity; (2) innovativeness of product architecture; (3) complexity of product architecture; (4) capability dispersion along the supply network; (5) rivalry among leading firms & suppliers; and (6) logistics costs. These findings contribute immensely toward a more contingent view of the mirroring hypothesis. However, the six clusters of contingent factors are arguably all from the supply side. In practice, managers certainly need to consider demand side issues to formulate effective product and organizational strategies (Priem et al., 2012). Thus, we may be missing opportunities to develop new knowledge from the demand side.

THEORY DEVELOPMENT

The proposed theory aims to account for how different demand characteristics influence the extent of mirroring between product and organization. Specifically, it is proposed that target customers' demands for product performance and reliability would impact the extent of mirroring. The following section first discusses the different approaches companies can take to make technological advances to establish these claims. Table 1 provides a summary of these approaches.

Two Approaches to Improve Product Performance

Modularity theory suggests there are two approaches to improving product performance. First, modular innovations within the established product architecture can improve overall product performance. Since the standardized component interfaces remain unchanged, multiple modular innovation efforts can proceed concurrently and autonomously (Langlois & Robertson, 1992) as long as they continue to conform to the standardized interfaces. In this case, modular products are indeed developed within

loosely coupled, modular organizational structures. This is the approach we observe in much of the history of the PC industry, with specialized firms focusing on industry-standard components within a well-established product architecture (e.g., Intel and AMD focus on x86 compatible CPUs; Asus and Gigabyte focus on x86 compatible motherboards).

The second approach achieves greater overall product performance by developing a new and more integrated product architecture. This approach embraces the “power of integrality” (Fixson & Park, 2008) or “synergistic specificity” (Schilling, 2000) and might be able to accomplish things that more modular systems cannot. However, it requires a more integral organizational structure to coordinate the higher level of interdependence across components. This strategy is evident in the bicycle drivetrain industry, where Shimano reduced its product modularity, developed a bicycle drivetrain system with tightly coupled components, and dominated the formerly competitive market by achieving superior product performance to its competitors (Fixson & Park, 2008).

It should be noted that both approaches to improving product performance are actually consistent with the mirroring hypothesis, i.e., modular innovations are developed within modular organizational structures, whereas integral product designs require integral organizations to develop.

The Third Approach

Observation of industry practice reveals another approach that is commonly used but has not received much attention in modularity research. Companies seeking to optimize product performance often carry out system fine-tuning - the precise mutual adjustments of component settings or configurations to improve product performance. Importantly, system fine-tuning does not entail modifications to component designs or standardized component interfaces. Fine-tuning only adjusts the settings of modular components within the range of variation permitted by the standardized interfaces.

Fine-tuning a computer system to serve a busy website, for example, may involve adjusting the settings of the networking module and database system running on the computer to maximize data throughput. It does not entail modifying the software source code or hardware design. Without deploying additional software or hardware resources, system fine-tuning can produce significant performance gains (e.g., Kamatkar et al., 2018).

System fine-tuning combines the advantages of the two approaches discussed earlier. It preserves the existing modular product architecture so companies can continue to benefit from using established interface standards to coordinate their product

development efforts. At the same time, it allows system builders to achieve a tighter integration across existing modular components to maximize system performance.

However, system fine-tuning does reduce the organizational benefits of product modularity. Particularly, fine-tuning requires knowledge about the inner workings of modular components and their nuanced interactions to create synergy across components. Thus, it violates the principle of information hiding. In other words, fine-tuning increases interdependence across modular components to some extent, despite preserving the existing modular product architecture. As a result, system fine-tuning requires more coordination across component development teams, i.e., fine-tuning reduces the extent of mirroring between product and organization.

Table 1 *Three Approaches to Improve Product Performance*

Approaches to Improve Product Performance	Impacts on Product Architecture	Impacts on Organizational Coordination	Implications to the Mirroring Hypothesis
Modular Innovation	Existing product architecture and the associated standardized component interfaces remain unchanged.	Multiple modular innovation efforts can proceed concurrently and autonomously without overt managerial coordination efforts.	Modular innovations are developed within modular organizational structures, consistent with the mirroring hypothesis.
Integrality	Existing product architecture and the associated standardized component interfaces are replaced by the new and more integrated product architecture.	A more integral organizational structure is needed to coordinate the higher level of interdependence across components.	Integral product designs are developed by integral organizations; consistent with the mirroring hypothesis
System Fine-Tuning	Existing product architecture and the associated standardized component interfaces remain unchanged.	Requires knowledge about the inner workings of other modular components and their nuanced interactions, therefore increasing the need for coordination across component development teams.	Product design remains modular but requires relatively more integrated organization to fine-tune; the extent of mirroring between product and organization is reduced.

Demand-Side Contingencies

Performance demands. Companies targeting customers with high performance demands can choose to develop their own proprietary architecture to maximize product performance. However, proprietary architecture does not benefit from economies of scale and can be at a significant cost disadvantage. For example, Sun Microsystems used to dominate the high-end computer workstation market with their proprietary SPARC CPU architecture and Solaris operating system but eventually lost the market to competitors building much cheaper systems based on the industry standard Intel x86 architecture and Microsoft's Windows operating system.

Alternatively, these companies can adopt industry-standard modular architecture and select the best-performing components from the market. However, their competitors can obtain the same components as well. Thus, the ability to perform system fine-tuning is among the most important sources of competitive advantage for these companies. As a result, their organizational structures would remain relatively more integrated to perform system fine-tuning. For example, these days, the market for high-end computer workstations is dominated by PC manufacturers such as Dell and HP. They use commodity PC components and carefully fine-tune their high-end computer workstations for demanding technical or scientific applications. Based on this reasoning, it is proposed:

Proposition 1: The extent of mirroring would be reduced for firms targeting customers with high performance demands.

Reliability demands. Product reliability is another demand characteristic that could reduce the extent of mirroring. For modular products, reliability issues often arise out of unintended incidental interactions across components (Ulrich, 1994). These insidious glitches often remain undetected through much of the product development (Sosa et al., 2004) and manifest themselves only after all the components have been built and put together. Since these incidental interactions cut across components, it requires collective efforts among multiple component development teams to jointly discover and resolve. Oftentimes reliability issues can only be resolved through painstaking system fine-tuning.

Reliability issues range from minor inconveniences (e.g., PC crashes) to catastrophic failures (e.g., plane crashes). Depending on the specific applications, product failures can result in drastically different economic losses, even for similar technical systems. For example, a computer system built for personal gaming (e.g., a flight simulator) and one intended as a part of an aircraft avionics system should have

different reliability demands, even if both are based on similar component technologies and architecture.

Customers facing potentially high economic losses in the event of product failures would demand product systems that are proven to be highly reliable. To serve these customers, companies should remain more integrated to detect and resolve as many unwanted component interactions as possible, even if the product architecture is highly modular. Thus, the extent of mirroring is expected to be reduced for these companies.

Proposition 2: The extent of mirroring would be reduced for firms targeting customers with high reliability demands.

EMPIRICAL CHALLENGE AND SOLUTION

Understanding complex phenomena requires that we hold some units of observation constant. Hoetker (2006) comments that it has been difficult to empirically test the mirroring hypothesis because we rarely observe design processes that differ in their degree of product and organizational modularity but not along other dimensions. To address this challenge, Hoetker (2006) used a unique empirical setting to control for confounding factors present in previous studies. Subsequent research has similarly used unique empirical settings to test the mirroring relationship (e.g., Argyres & Bigelow, 2010; Cabigiosu & Camuffo, 2012; Furlan et al., 2014; MacCormack et al., 2012).

The model of mirroring with demand-side contingencies presents an additional challenge. To empirically test demand contingencies, we need to control for confounding factors and, at the same time, allow variance in demand conditions. To address this issue, this study observes the organizational design choices of computer systems integration firms using the industry-standard Intel x86 computer architecture, effectively holding product architecture constant in terms of software and hardware compatibility. Importantly, Intel's x86 architecture is not synonymous with IBM PC compatible since x86 computer architecture is also widely used in a large variety of computer systems beyond personal computing. Thus, this empirical context allows the needed variance in demand characteristics. In addition, the long-time market dominance of x86 architecture results in the proliferation of commercial off-the-shelf (COTS) components for all the components needed to build a functioning computer system. Even for more specialized use cases (e.g., avionics systems, defense systems, and telecommunication devices), systems integrators still have COTS components readily available from the marketplace¹.

¹ This claim is verified by interviews with practitioners in the industrial computer manufacturing segment. Interviewees reported that almost all components they chose to develop internally have COTS counterparts available. These practitioners also provided catalogs for specialized COTS

Consequently, systems integrators adopting x86 architecture can easily mix and match modular components from a wide variety of readily available COTS components to build computer systems that serve different use cases. This combinative flexibility is one of the key benefits suggested by the proponents of modularity (Baldwin & Clark, 1997; Schilling, 2000). Furthermore, the proliferation of COTS components also means that systems integration firms do not need to possess component development capabilities to build functioning computer systems. In fact, building x86-compatible computer systems has become so accessible that even people without much technical knowledge and resources can manage to do so easily. The vibrant DIY PC building community is a testament to the widespread access to this standard architecture. This high degree of vertical specialization is consistent with the prediction of the mirroring hypothesis (Baldwin & Clark, 2000; Sanchez & Mahoney, 1996). Therefore, in this empirical context, decisions to not use readily available COTS components can be interpreted as a move away from spot markets towards integration, which is, therefore, a case of reduced mirroring or deviation from the prediction of mirroring. Accordingly, two hypotheses can be derived in this empirical context to test the propositions presented earlier:

Hypothesis 1: An increase in target customers' performance demand increases a systems integration firm's likelihood of deviating from using COTS components.

Hypothesis 2: An increase in target customers' reliability demand increases a systems integration firm's likelihood of deviating from using COTS components.

DATA AND METHOD

To test these hypotheses, this study conducts a quantitative cross-sectional study of computer systems integrators' decisions to deviate from using readily available COTS components, which indicate decreased mirroring. Interviews with three computer systems integrators² in Silicon Valley supplement the quantitative study.

Sample

components.

² The three systems integrators interviewed were selected from different industry segments. One systems integrator produces industrial computer systems for a variety of specialized use cases in industrial or otherwise harsh environments. The second systems integrator produces Linux-based computer servers and workstations for high-performance computing. The third systems integrator specializes in servers and desktop computers for business applications. All of these firms produce systems fully compatible with the Intel x86 standard.

The proliferation of x86 computer architecture into a large variety of industries presents a challenge for data collection. No single directory lists all systems integration firms adopting the x86 standard because these firms operate in different industries. To construct the sample of qualified systems integrators, I identified the SIC codes for 7 example firms that use the x86 standard to implement computer systems in a variety of industries (personal computer, high-performance engineering workstation, server computer, industrial computer, defense system, telecommunication device, and security device). With the 5 SIC codes identified for the 7 example firms, Hoover's Industry Directory was used to identify 14,214 firms in the 6 largest U.S. high-tech clusters, according to reports³ from the Milken Institute and Brookings Institute. These 6 clusters account for 16.4% of North American employment and 25.4% of North American wages in high-tech manufacturing and services industries⁴. These firms are then screened to identify systems integrators that meet the following conditions:

- (1) The company builds fully integrated computer systems; firms that only build partially assembled systems (known as "barebone" systems) that require further integration were excluded. This condition ensures that the included firm is directly responsible to the customers for the overall system performance and reliability.
- (2) The computer systems are fully compatible with Intel x86 architecture. This condition ensures that firms in the sample do have the choice between readily available x86-compatible COTS components vs. internal development or other sources of custom-design components.

This screening process identified a sample of 177 strategic business units (out of 173 firms) that sell fully integrated computer systems based on Intel x86 compatible architecture.

Dependent Variable

A computer system can be conceptualized as a three-layer stack. At the bottom is the hardware layer, which consists of various semiconductor chips integrated on a printed circuit board called the "motherboard." In the middle is the system software layer, which includes the operating system (e.g., Microsoft Windows, Linux) and various hardware-component controlling programs called "drivers." Hardware component firms develop these drivers in accordance with pre-defined interface standards so that their components can be compatible with the rest of the computer

³ The two reports referenced are North America's High-Tech Economy: The Geography of Knowledge-Based Industries by the Milken Institute and High-Tech Specialization: A Comparison of High Technology Centers by the Center on Urban and Metropolitan Policy at the Brookings Institute.

⁴ According to the report by the Milken Institute.

system. At the top is the application software layer, which includes packaged software programs (e.g., Microsoft Office, Internet browsers) that interact directly with the users. Packaged software programs usually require an operating system to function. They are developed in accordance with the operating system's application programming interface (API), which ensures compatibility with the computer system.

Since x86 architecture is highly modular and standardized, and COTS components are readily available for all kinds of use cases, systems integrators, in theory, do not need to possess the capabilities to develop or modify any component across these three layers. Compatible hardware and software components from the spot markets are all supposed to "plug and play." Thus, observation of internal development or modification activities in any of the three layers by a systems integrator indicates a deviation from perfect mirroring.

Along with two industry experts, data for this variable were collected by reviewing the company's product catalogs. Since systems integrators have an incentive to advertise their differentiating capabilities, it was easy to observe instances of deviation. We contacted those companies that did not provide sufficient information in their product catalogs to determine the value of this variable. The indicator variable DEVIATION is set to 1 if a systems integrator is observed to engage in component development or modification activities in any of the three layers. For example, if a systems integrator develops its own driver program for a hardware component instead of using the generic driver program provided by the component vendor, the indicator variable DEVIATION is set to 1; or if a systems integrator works with packaged software vendors to optimize or certify otherwise compatible packaged software, the indicator variable DEVIATION is also set to 1. Since the value of this variable is based on objective observation, the three coders achieved high agreement in the initial coding (agreement for 163 of the 177 strategic business units, or 92.09% agreement). We resolved the cases of disagreement after discussion.

Independent Variables

To measure the performance and reliability demands of the focal firm's target customers, the two industry experts and the author rated the company's product catalogs, websites, or any other available marketing materials we could obtain. We developed and pretested the initial coding procedures with 20 firms that were excluded from the final sample due to their adoption of non-x86 computer architectures but otherwise competed in similar market segments as the included firms. However, it was determined that the initial operationalization of the two constructs, namely target customers' performance and reliability demand, lacked distinctiveness. Coders often confused the two constructs. For example, in many cases, if a computer system performs too poorly,

the resulting low performance could result in severe economic loss to the customer in a manner similar to system crashes, i.e., insufficient performance can result in the same devastating economic loss as total loss of performance in demanding use cases. In these use cases, the coders tended to code it as both high performance and reliability demands.

In order to improve distinctiveness, the two constructs were subsequently recoded with new operationalizations. In particular, reliability demand was operationalized strictly in terms of unexpected failure to meet design specifications. Insufficient computing power, so long as it is not a result of unexpected failure to meet design specifications, is therefore made conceptually distinct from insufficient reliability. The new operationalizations were tested with another 20 firms not included in the final sample. The coders discussed discrepancies in the coding and refined the coding protocol accordingly.

To assess inter-coder reliability with 3 coders and interval scale, the appropriate measure is Krippendorff's alpha (Krippendorff, 2004). For target customers' performance demand, Krippendorff's alpha among the 3 coders is 0.763; for target customers' reliability demand, Krippendorff's alpha among the three coders is 0.842. These reliability measures are above the common threshold of 0.7 in content analysis research (Krippendorff, 2004). The independent variable PERFORMANCE is set to the average of the values coded by the three experts. Similarly, the independent variable RELIABILITY is set to the average of the values coded by the three experts.

Control Variables

Although this study aims to determine the impact of demand characteristics on a firm's decision to forgo using COTS components, other factors may also impact this decision. For instance, production volume can influence the likelihood of deviating from using COTS components due to its impact on the overall cost structure. There are fixed costs associated with product development. Firms that choose to forgo using readily available COTS components have to bear these fixed costs. Therefore, there needs to be sufficient volume for internal component development to be an economically viable option. In addition, firms with high production volume can potentially achieve significant savings if the components are custom designed to reduce the cost of production by eliminating some unwanted features from industry-standard components. At large volumes, even a slight decrease in component cost can easily outweigh the fixed costs of custom design and even result in additional profits. Thus, the production volume of the integrated systems is included as a control variable to ensure that the observed relationships between the dependent variable and the theoretical variables are not influenced by it.

The exact production volume is difficult to measure consistently across all the systems integration firms in the sample. Market research firms like International Data Corporation and Gartner provide unit sales estimates for the large PC vendors; however, for systems integrators in specialized categories, such information is difficult to obtain. Therefore, the number of employees in Hoover's Industry Directory serves as a proxy for a firm's production volume. Due to the highly skewed distribution of the number of employees within the sample, the natural logarithm of the number of employees was used as the measure of production volume for this research.

In addition, if a system integration firm also sells internally developed components (not just retail COTS components) to other systems integrators, the firm is likely to prefer internally developed components over other COTS components regardless of demand characteristics. Participation in the component business also indicates the firm possesses component development capability independent of its systems integration business. Since capabilities influence firms' vertical boundary choices (Leiblein & Miller, 2003), participation in the component business should also be controlled.

Moreover, there are reasons to believe that firms selling integrated computer systems to military and other government agencies might organize their component development differently due to the certification requirements in accordance with relevant military standards and specifications. Therefore, firms that have obtained certifications for military standards are also controlled.

Table 2 lists all the variables and their operationalizations. Correlations and descriptive statistics for all variables included in the models are presented in Table 3.

Table 2 *Conceptual Variables and Corresponding Empirical Data*

Conceptual variable	Empirical data	Variable name
Control variable	Is this firm also selling system components at either hardware, system software, or application software level to other customers (0/1)	COMPONENT BUSINESS
Control variable	Are this firm's products certified for relevant United States Defense Standards and Specifications (0/1)	MILITARY
Control variable	Natural log of the number of employees in the firm (or in the specific strategic business unit for multi-divisional firms)	PRODUCTION VOLUME
Control variable	A categorical variable created by median splitting production volume (0=low; 1=high)	VOLUME_DUMMY
<i>Independent variables</i>		
Target customer's performance demand	Average of the firm's target customer's system performance demand coded by the three experts	PERFORMANCE
Target customer's reliability demand	Average of the firm's target customer's system reliability demand coded by the three experts of	RELIABILITY
<i>Dependent variable</i>		
Deviation from perfect modularity	Does the firm deviate from using commercially available, "off-the-shelf" components at either hardware, system software, or application software level (0/1)	DEVIATION

Table 3 *Descriptive Statistics and Correlations*

	Mean	S.D.	Min.	Max.	1	2	3	4	5	6	7
1. DEVIATION	0.51	0.5	0	1	1						
2. COMPONENT BUSINESS	0.15	0.36	0	1	0.255	1					
3. MILITARY	0.06	0.24	0	1	0.157	-0.109	1				
4. PERFORMANCE	3.85	2.47	1	10	0.572	0.229	0.015	1			
5. RELIABILITY	4.58	2.91	1	10	0.712	0.151	0.327	0.553	1		
6. log(EMPLOYEES)	3.42	2.23	1.1	11.39	0.516	0.556	0.049	0.417	0.414	1	
7. VOLUME_DUMMY	0.51	0.5	0	1	0.57	0.255	0.157	0.488	0.553	0.715	1

Model Specification

A binary choice logit model was employed to assess the relationship between a set of covariates and whether or not a systems integration firm deviates from using COTS components. Specifically, the binary choice model assumes a firm's decision to deviate is determined by an unobservable, latent variable explained by several regressors. The observation of a firm's deviation decision is therefore assumed to indicate whether the value of the latent variable exceeds a threshold value. This model specification produces the following multivariate statistical model:

$$\text{DEVIATION} = \beta_0 + \beta_1\text{-3 Controls} + \beta_4 \text{ PERFORMANCE} + \beta_5 \text{ RELIABILITY} + \varepsilon$$

RESULTS

Table 4 summarizes the coefficient estimates and goodness-of-fit measures for the 4 logit models used to test the hypotheses. These models estimate the effects of the covariates on the probability that a systems integration firm will deviate from using readily available COTS components. Since this industry is well known for its high level of product modularity and a large variety of COTS components are available for all the needed system components, deviation from using COTS components can be interpreted as a deviation from perfect mirroring between product and organization. Thus, a positive coefficient indicates that the variable is positively related to the probability of deviation from perfect mirroring.

Model 1 is the baseline model with only the control variables included. Only PRODUCTION VOLUME is statistically significant. The coefficient estimate is positive, as expected. Model 2 and Model 3 introduce the independent variables PERFORMANCE and RELIABILITY, respectively. The coefficients are all highly significant and are all positive, as predicted. Model 4 introduces all independent and control variables. The coefficients for all the independent variables are statistically significant and all positive, as predicted. The results from these models provide strong support for the two hypotheses.

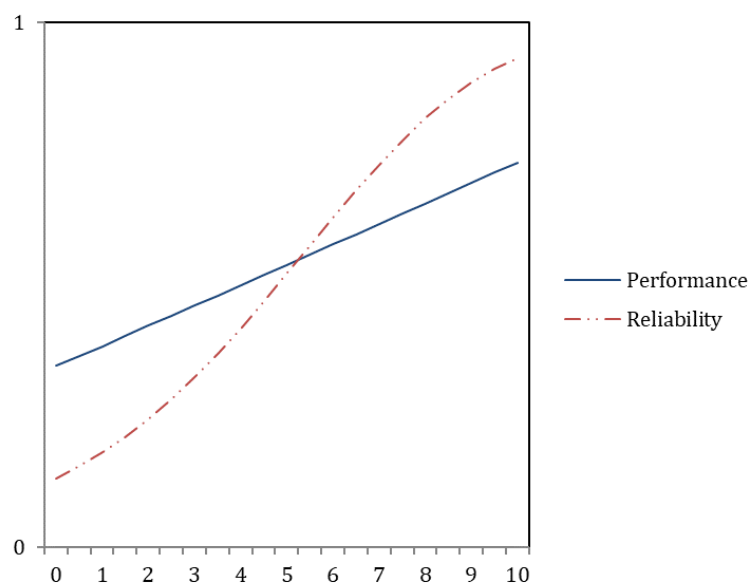
To determine the net effects of PERFORMANCE and RELIABILITY on the likelihood of deviation from perfect mirroring, the coefficients obtained from Model 4 were used to plot the predicted probabilities of deviation against the two independent variables, with all other variables evaluated at their mean values. Figure 1 indicates that both PERFORMANCE and RELIABILITY positively impact a systems integration firm's probability of deviating from perfect mirroring. Moreover, RELIABILITY appears to have a stronger marginal effect on the probability of deviating for most of the range in the dataset.

Table 4 Results of Logistic Regression Analyses for Deviation from Perfect Modularity

	Model 1	Model 2	Model 3	Model 4
COMPONENT	0.506	0.682**	0.223	0.530
BUSINESS	(1.20)	(2.82)	(0.18)	(0.39)
MILITARY	1.125	1.249*	-0.976	-0.453
	(1.32)	(2.24)	(-1.07)	(-0.51)
PRODUCTION	0.872***	0.640***	0.517***	0.517***
VOLUME	(5.84)	(6.50)	(4.35)	(3.47)
PERFORMANCE		0.558**		0.358**
		(3.69)		(2.84)
RELIABILITY			0.732***	0.639***
			(11.50)	(6.50)
Constant	-2.710***	-4.170***	-4.889***	-6.079***
	(-10.26)	(-7.43)	(-6.04)	(-5.96)
Observations	177	177	177	177
Adjusted Count R ²	0.477	0.628	0.663	0.686
McFadden's R ²	0.279	0.415	0.529	0.568
Log-likelihood	-88.466	-71.745	-57.738	-53.008

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 1 Predicted Probabilities

Robustness Checks

To assess the robustness of the results, I ran additional models with interactions between variables. Because customers with high performance or high reliability demands are underserved by the mainstream market, these customers would be willing to pay a price premium to obtain the high performance or high reliability systems they need (Christensen et al., 2002). This price premium reduces the production volume needed to justify the fixed costs associated with internal component development. In other words, the positive effects of customer's performance and reliability demands on the likelihood of deviation should be larger for firms with higher production volume.

According to Hoetker (2007), the marginal effect of an interaction between two variables in a logit model is not simply the coefficient for their interaction. Due to the nonlinear nature of logit models, the magnitude and even the sign of the marginal effect can differ across observations (Huang & Shields, 2000). Thus, interpretation of interactions is more complicated in logit models. To make it easier to assess interactions, the continuous variable PRODUCTION VOLUME was transformed into a categorical variable by median splitting into low and high categories. Model 5 replaces the continuous variable PRODUCTION VOLUME in Model 4 with the categorical VOLUME DUMMY variable. Results from Model 5 are consistent with results from Model 4, both in terms of coefficient estimates and goodness-of-fit measures, suggesting that the categorical variable can be an acceptable substitute for the continuous variable. This model specification produces the following multivariate statistical model:

$$\begin{aligned} \text{DEVIATION} = & \beta_0 + \beta_1\text{-2 Controls} + \beta_3 \text{ VOLUME DUMMY} + \beta_4 \\ & \text{PERFORMANCE} + \beta_5 \text{ RELIABILITY} + \beta_6 \\ & \text{VOLUME_DUMMY} \times \text{PERFORMANCE} + \beta_7 \\ & \text{VOLUME_DUMMY} \times \text{RELIABILITY} + \varepsilon \end{aligned}$$

Table 5 summarizes the coefficient estimates and goodness-of-fit measures for the 3 logit models used to assess the interaction between production volume and the two independent variables. Model 6 includes only the independent variable PERFORMANCE and the interaction term. Consistent with Model 4, the coefficient for PERFORMANCE is statistically significant and positive. However, the interaction term is not statistically significant in this model. Model 7 includes only the independent variable PERFORMANCE and the interaction term. Consistent with Model 4, the coefficient for RELIABILITY is statistically significant and positive. However, the interaction term is also not statistically significant in this model. Model 8 is the full model with both independent variables and interaction terms included. Coefficients for

RELIABILITY and the interaction term between RELIABILITY and VOLUME DUMMY are statistically significant. Coefficients for PERFORMANCE and the interaction term between PERFORMANCE and VOLUME DUMMY are not statistically significant.

Table 5 *Results of Logistic Regression Analyses for Deviation from Perfect Modularity*

	Model 4	Model 5	Model 6	Model 7	Model 8
COMPONENT	0.530	1.873*	1.193***	1.628*	1.961*
BUSINESS	(0.39)	(2.17)	(3.31)	(2.55)	(2.42)
MILITARY	-0.453	-0.471	1.188*	-1.008	-0.469
	(-0.51)	(-0.73)	(2.01)	(-1.44)	(-0.65)
PRODUCTION	0.517***				
VOLUME	(3.47)				
VOLUME		1.218***	3.074**	0.645	0.733
DUMMY		(3.62)	(2.68)	(1.23)	(0.53)
PERFORMANCE	0.358**	0.320*	0.696**		0.476
	(2.84)	(2.45)	(2.78)		(1.58)
RELIABILITY	0.639***	0.619***		0.635***	0.439***
	(6.50)	(8.45)		(5.54)	(4.04)
VOLUME DUMMY *			-0.338		-0.240
PERFORMANCE			(-1.40)		(-0.70)
VOLUME DUMMY *				0.171	0.317**
RELIABILITY				(1.55)	(2.63)
	(-5.96)	(-7.70)	(-4.81)	(-8.31)	(-4.17)
Observations	177	177	177	177	177
Adjusted Count R ²	0.686	0.698	0.651	0.651	0.733
McFadden's R ²	0.568	0.544	0.410	0.516	0.554
Log-likelihood	-53.008	-55.865	-72.401	-59.342	-54.656

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Interpretation is further complicated by the fact that the significance of the interaction effect in logit models cannot be determined by just the significance of the interaction coefficient (Hoetker, 2007). To help interpret the results obtained, this study followed Hoetker's (2007) recommendation to produce graphical presentations in order to provide the most complete understanding of the interaction's effect. In addition, this study also followed Zelner's (2009) recommended simulation-based approach, as

implemented in STATA's marginsplot command, to produce the 95% confidence interval in Figures 2(a) and 2(b) to help interpret the interactions.

Even though the coefficient for the interaction term between RELIABILITY and VOLUME DUMMY is statistically significant, Figure 2(b) shows the 95% confidence intervals are clearly separated only between the RELIABILITY = 5.5 and RELIABILITY = 8.5. This pattern indicates that statistically, the interaction effect is significant only in a specific range. These results suggest that only reliability demand reduces the production volume needed to justify the fixed costs associated with internal component development, and only over a specific range.

Figure 2(a). Interaction between PERFORMANCE and VOLUME DUMMY

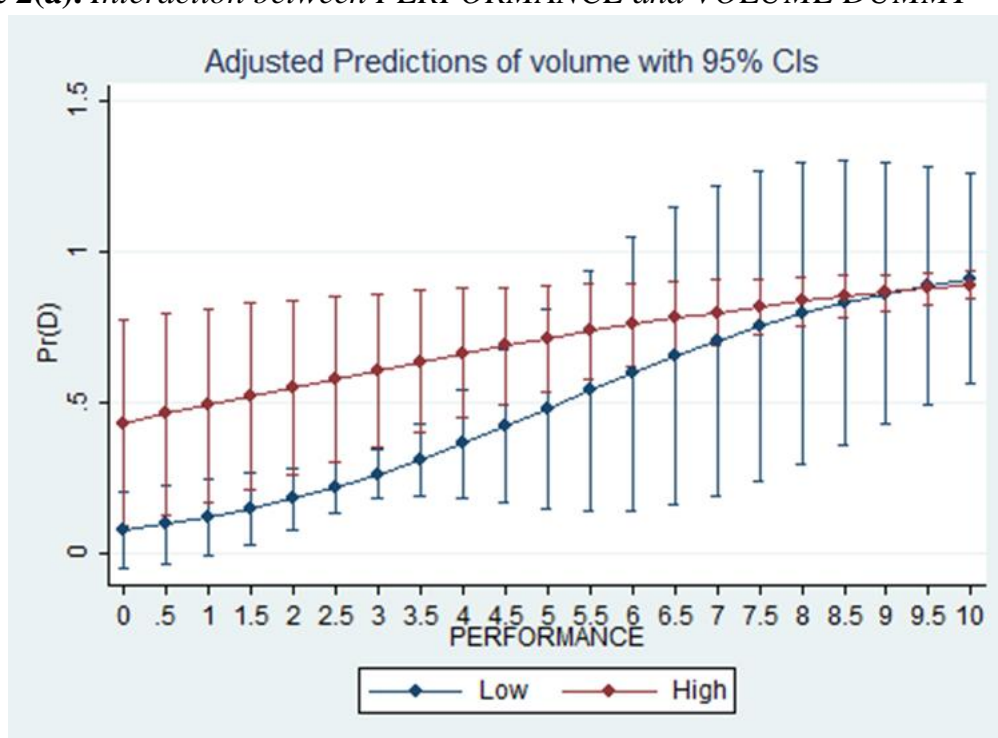
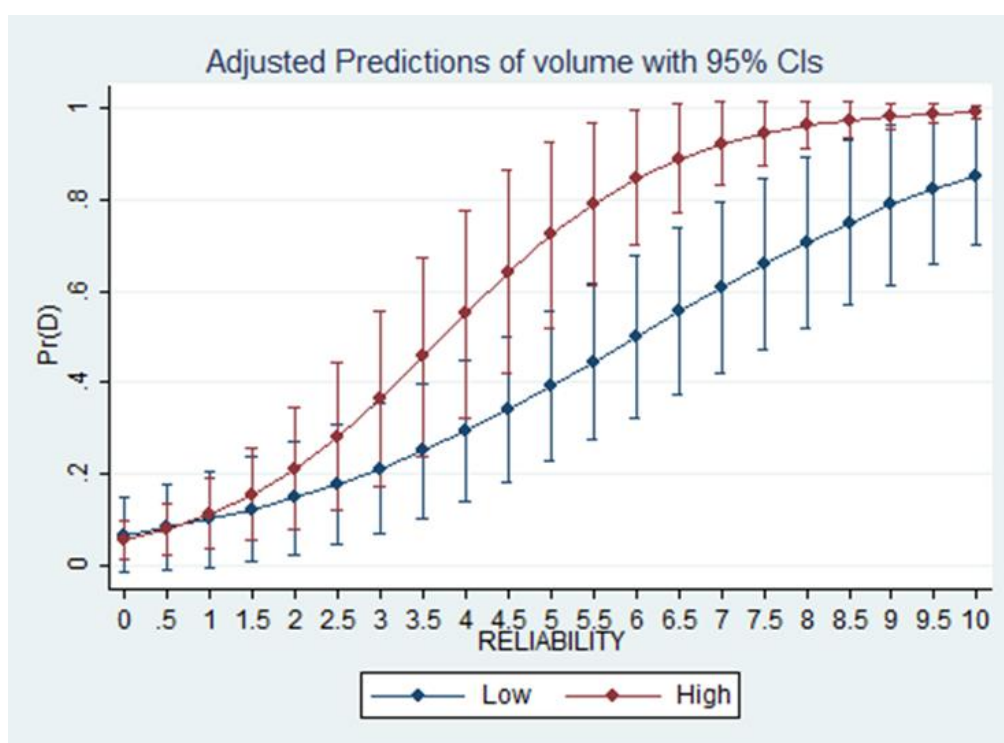


Figure 2(b). *Interaction between RELIABILITY and VOLUME DUMMY*

In addition, additional models were used to assess the interaction between the independent variables with the control variable COMPONENT BUSINESS. Participation in the component business indicates possession of component development capability, which might interact with the two independent variables in their impact on the probability of deviating from perfect mirroring. Firms participating in the component business should be more likely to deviate from using COTS components from the market, given the same level of performance and reliability demand. This model specification produces the following multivariate statistical model:

$$\begin{aligned} \text{DEVIATION} = & \beta_0 + \beta_1\text{-3 Controls} + \beta_4 \text{ PERFORMANCE} + \beta_5 \text{ RELIABILITY} \\ & + \beta_6 \text{ COMPONENT BUSINESS} \times \text{PERFORMANCE} \\ & + \beta_7 \text{ COMPONENT BUSINESS} \times \text{RELIABILITY} + \varepsilon \end{aligned}$$

Table 6 summarizes the coefficient estimates and goodness-of-fit measures for the 3 logit models used to assess the interaction between participation in component business and the two independent variables. Similar to the interaction with production volume, the results only indicate an interaction between RELIABILITY and COMPONENT BUSINESS. However, contrary to expectation, the sign of the interaction terms between RELIABILITY and COMPONENT BUSINESS is consistently negative.

In summary, the empirical results strongly support the two hypotheses. Increases in a production volume increase the likelihood of using custom-designed components instead of readily available COTS components. Increases in target customers' performance and reliability demand reduce the extent of mirroring for systems integration firms. As expected, target customers' reliability demand interacts with production volume, while target customers' performance demand does not appear to interact with production volume.

Table 6 *Results of Logistic Regression Analyses for Deviation From Perfect Modularity*

	Model 9	Model 10	Model 11
COMPONENT BUSINESS	1.518 (1.80)	3.463** (2.53)	4.835* (2.38)
MILITARY	1.252* (2.29)	-1.387 (-1.33)	-0.827 (-0.88)
PRODUCTION VOLUME	0.638*** (6.45)	0.479*** (6.08)	0.446*** (4.77)
PERFORMANCE	0.578*** (4.11)		0.434** (3.06)
RELIABILITY		0.885*** (7.00)	0.835*** (4.46)
COMPONENT BUSINESS * PERFORMANCE	-0.242 (-1.55)		-0.170 (-0.93)
COMPONENT BUSINESS * RELIABILITY		-0.664** (-2.63)	-0.726** (-2.68)
Constant	-4.237*** (-8.03)	-5.477*** (-5.66)	-7.203*** (-4.59)
Observations	177	177	177
Adjusted Count R ²	0.640	0.698	0.721
McFadden's R ²	0.416	0.553	0.598
Log-likelihood	-71.556	-54.864	-49.271

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

DISCUSSION

In the mainstream modularity literature, product modularity is said to be associated with loosely coupled organizations that use market-based coordination mechanisms to coordinate their product development activities (Baldwin & Clark, 2000; Sanchez &

Mahoney, 1996). This study explains why firms adopting standardized modular product architecture sometimes deviate from this prediction. This study proposed and found strong empirical support that systems integration firms would refrain from perfect mirroring if they target customers with high performance or high reliability demands, because these firms are more reliant on system fine-tuning to achieve the desired product qualities.

Untangling Different Demand Contingencies

The computer industry has become the paradigmatic example of the mirroring hypothesis (e.g., Baldwin & Clark, 2000; Langlois, 1992; Langlois & Robertson, 1992). Finding clear evidence of demand contingencies in this paradigmatic context provides strong support for the contingent nature of the mirroring hypothesis. Furthermore, the empirical results also indicate that target customers' reliability demand has a greater and more consistent impact on the mirroring relationship than target customers' performance demand. Thus, different demand-side factors impact the mirroring relationship in different ways, suggesting the need for more careful theoretical and empirical investigation to untangle the different mechanisms.

Theoretically, the extant literature has suggested two alternative ways of improving product system performance: 1.) modular innovation accessible through the component market; 2.) architectural innovation as the result of the standard disruption. The discussion earlier suggests a third alternative: namely, through careful fine-tuning or "tweaking" the system. The equifinality in performance improvement mechanisms suggests that systems integrators would select the least costly approach. Empirically, knowledge about this industry provides the cost explanations to the observed differential impacts of performance and reliability demands. Specifically, the underpinning semiconductor technology has achieved a persistent doubling of performance approximately every two years, an observation known as Moore's Law (Moore, 1965). This trajectory translates to million-fold cost reductions and performance improvements in one of the performance-critical components of a computer system (i.e., CPU). The unique exponential performance growth and cost reduction diminish the cost-effectiveness of system fine-tuning as a way to attain marginal performance gain, which helps explain the weaker impact of performance demand on mirroring in this context.

System reliability, on the other hand, does not automatically improve as the underpinning component technologies improve. In addition, system reliability is also relative to the unique use case for which the integrated product system is intended. Thus, unlike performance, reliability is more specific to the particular target customers' needs since each unique use case can potentially introduce product deployment conditions that

had not been considered when the component standard was defined. Systems integrators pursuing high reliability thus have to resort to tighter organizational integration to discover and contain incidental component interactions that cause reliability issues, even when the product architectures are highly modular.

Different Kinds of System Fine-Tuning

The differential impacts of performance and reliability on mirroring also reveal that there are, in fact, two different kinds of system fine-tuning. On the one hand, fine-tuning for better system performance is more often guided by existing knowledge of component interactions, i.e., fine-tuning for better performance is enabled by extant architectural knowledge. The improved system performance is the intended consequence of the fine-tuning efforts. On the other hand, fine-tuning for better reliability proceeds as an experiment to uncover unintended and, therefore, unknown component interactions, i.e., fine-tuning for better reliability is, in essence, an organized search effort for new architectural knowledge, which requires a more integrated organizational structure. Fine-tuning for reliability, therefore, has a greater impact on mirroring between product and organization.

LIMITATIONS

This study has some limitations. First, reliance on subjective expert coding can potentially introduce measurement issues for the key variables. Even though the coding procedure produced acceptable inter-coder reliability, reliability does not guarantee to construct validity. The dichotomous coding for the dependent variable also reduces the observed variation in the statistical analysis. Since deviation from perfect mirroring was observed across the three-layer stack (i.e., hardware, system software, and application software), a multinomial logit model could have been employed to exploit the observed variation more. However, the limited sample size prevented such an approach.

Second, there are reasons to believe that the constructed sample does not cover all industries that adopt Intel x86 architecture. Anecdotal evidence indicates widespread adoption of this technology in the medical device and defense industries. However, these industries were not well represented in the sample because firms in these industries are reluctant to disclose their product details due to security or liability concerns. Therefore, the constructed sample might be biased, although interviewees at the three systems integrators did provide similar accounts for their engagements in these industries.

Finally, alternative explanations besides system fine-tuning cannot be fully ruled out due to the limitations of the empirical design. Specifically, differential capabilities in component technologies might better explain firms' vertical boundary choices

(Leiblein & Miller, 2003). Even though the variable COMPONENT BUSINESS was included to control for this alternative explanation, the control variable is not statistically significant, suggesting that systems integrators' participation in component business is perhaps not a good measurement for component capabilities in this empirical context. A related alternative explanation reinforces this concern. Perhaps a systems integrator forgoes using readily available COTS components because it possesses unique, superior component development capabilities. This firm might be able to extract monopoly rent if it chooses to always bundle the component with the rest of the system. For example, Apple developed the M1 chip that has been shown to be superior to competitors' offerings in many ways. However, Apple does not sell M1 chips to other system builders. In this case, lack of participation in component business is, in fact, the result of superior capabilities.

Interviews with industry practitioners suggest an additional alternative interpretation of the empirical results on reliability. Customers intending to deploy in mission-critical applications sometimes demand component service and replacement availability far exceeding the typical time period provided by COTS component vendors. These customers are unwilling to take on the uncertainty of discontinued component service or replacement availability because once they certify the system for their mission-critical applications, they would prefer not to change any detail of their deployments. Thus, even without the need to fine-tune for better reliability, systems integrators might still internalize the component development tasks in order to satisfy the extended service and availability expectations. However, these customers also typically demand high reliability in their systems. Therefore, this study's current empirical design is unable to tease apart these two mechanisms.

CONCLUSIONS

This study contributes to the modularity literature in several ways. First, this study proposes demand-side contingent factors and provides empirical evidence that helps reconcile the mainstream narratives of mirroring and the emerging revisionist perspective that challenges the mainstream predictions. As discussed earlier, there is an inherent tension in modular design as systems integration firms try to improve overall product performance. These firms can rely on modular innovations in performance-critical components to deliver better overall performance while preserving the benefits of having established interface standards. However, this approach places an upper limit on performance that is inherent in the current architecture. In addition, this approach also means the system integrators are dependent on external component suppliers to improve performance-critical components. Alternatively, these firms can choose to disrupt established interface standards with architectural innovations, which can

potentially provide significantly better performance but at a much higher cost and risk of failure.

This study suggests a third commonly used approach of system fine-tuning, which combines the advantages of the first two approaches. The reliance on system fine-tuning as a mechanism to optimize performance within current product architecture provides the demand-side contingencies that reconcile the long-standing debate. Firms that rely more on system fine-tuning are expected to have reduced mirroring between product and organization.

Second, the study reveals that system integration can entail much more than just physical assembly of modular components. For some use cases, extensive post-assembly system fine-tuning is essential to deliver the performance and reliability demanded by the customers. This finding is consistent with the systems integration literature (Brusoni, 2005; Brusoni & Prencipe, 2001; Brusoni et al., 2001), maintaining that there is no one-to-one mapping between product architecture and organizational structure. The theoretical mechanisms discussed in this study provide a useful link between the mainstream modularity literature that focuses more on the benefits of modularity and the systems integration literature that focuses on the challenges of integration.

Lastly, this study provides an empirical analysis of how demand heterogeneity contributes to firm heterogeneity. Consistent with Priem and coauthors' (2012) observation, researchers have not given sufficient attention to demand-side issues. This study is the first to the author's knowledge that empirically examines how to target customers' demands impact the mirroring relationship between product and organization. Future research can further explore how different demand factors impact the mirroring relationships differently, shedding more light on how managers manage the interactions between the technologies under development and the organizations that develop these technologies.

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