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Product Architecture and Intra-Firm Coordination: Theory and Evidence

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Abstract

Product architecture plays a critical role in the product development process. How does the nature of product architecture affect the quality of the product? To address this question, we make a distinction between system-level and part-level quality, and then posit the existence of a key trade-off in which greater integrality of a product's architecture enhances its system-level quality, but produces the undesirable side-effect of increasing the degree of interdependence in component design. We hypothesize that when engineers' coordination capability is relatively high, the former (positive) effect outweighs the latter (negative) effect so that greater integrality increases the product's overall quality; conversely, lower coordination capability results in reduced overall quality. We find empirical support for this hypothesis by analysing a set of unique data collected through a firm-level survey administered in Japan. We also present the implications of our findings for managers making decisions about product design.

JEL Classification: M10, M50

Keywords: Component interactions, system-level quality, integrality, intra-firm coordination, modularity, part-level quality, product architecture, product design

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1. Introduction

Product development (or product design) is an important element in value-creating activities,[1] and product architecture plays a critical role in the product development process. The seminal work by Ulrich (1995) generated burgeoning interest in the role of product architecture, resulting in a growing body of research focusing on this concept (see Krishnam and Ulrich (2001) and Fixson (2005) for extensive reviews).

Product architecture is the assignment of the functional elements of a product to the building blocks of the product (Ulrich and Eppinger, 2012, p.184). It defines the way in which products as a system are divided into subsystems and how the interfaces among these subsystems are defined (see, e.g., Baldwin and Clark, 2000). A key distinction in the typology of product architecture is between a *modular architecture* and an *integral architecture* (Ulrich, 1995). In a modular architecture, one function of a product tends to be mapped into one component of the product (one-to-one mapping). Further, components connected by an interface are relatively independent in the sense that a change in the design of one component does not require many changes to the designs of other components. In contrast, in an integral architecture, the mappings between functions and components are more complex (non-one-to-one) and the designs of components connected by interfaces are closely interdependent (Ulrich, 1995; Fujimoto, 2001). Integrality and modularity are relative properties of product architecture. Products are rarely strictly modular or integral. Rather, products exhibit either more or less integrality/modularity than comparable products (Ulrich and Eppinger, 2012).

How does the integrality of a product's architecture affect the quality of the product? To address this question, we break down product quality (*overall quality*) into *system-level* and *part-level qualities*. Following Ulrich (1995, p. 432), we define part-level qualities as qualities that arise only from the properties of a local region of the product (i.e., at a part or component level), and system-level qualities as qualities that arise from the physical properties of most, if not all, of the components of the product.[2] We investigate the determinants of system-level and part-level qualities.

The distinction between system-level and part-level qualities reveals an important trade-off associated with integral architecture. That is, a higher degree of integrality in a product's architecture increases its system-level quality, but higher integrality also increases interdependence between different components, making it difficult to optimize part-level qualities. Below, we explain this trade-off using an illustrative example.[3] Consider a product that performs three functions, denoted by

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[1] Value-creating activities consist of technology development, product design, manufacturing, marketing, distribution, and services, based on a value-chain model proposed by McKinsey and Company (Barney, 2002; Grant, 1991). See also Clark and Fujimoto(1990)(1991).

[2] To be precise, Ulrich uses terms "performance characteristics" instead of "qualities".

[3] This illustrative example is based on the explanation given in Section 7 of Ulrich (1995).

A, *B*, and *C*. Suppose that the quality of the product is determined by primarily two factors: (i) the degree to which the product performs these three functions well, and (ii) the size of the product (the smaller the better). Under modular architecture, each function is mapped into one component (one-to-one mapping); function *A* is implemented by component *a*, function *B* is implemented by component *b*, and function *C* is implemented by component *c*. Furthermore, the design of each particular component does not affect the designs of other components. Component-function matching is easy under modular architecture.

The size of the product can be reduced by increasing the degree of integrality in the product's architecture. One strategy to reduce the size of the product is function sharing. For example, by letting function *B* be jointly implemented by components *a* and *c*, the product can eliminate component *b*, which would help reduce the size of the product. Function sharing, however, creates interdependence between the design of components *a* and *c* since they jointly perform function *B*. The other strategy is geometry nesting, in which components are placed in a smaller physical space. The shape of one component would then be affected by the shapes of other components because they must be situated in a limited physical space, necessitating interdependence of the component design.

Higher integrality in a product's architecture increases interdependence between the designs of different components. How does the greater degree of interdependence affect the quality of the product? Development of complex products involves multiple employees or teams (see, for example, Sosa, Eppinger, and Rowles, 2003, 2004). More precisely, the product development process of a complex product involves multiple engineers (or groups of engineers), where each engineer (or group of engineers) is assigned to design a component (or a set of components) of the product. In such cases, the higher interdependence of component design associated with greater architectural integrality increases the difficulty of coordinating design activities.

Real world examples may aid in understanding the issue. A familiar case would be multifunctional, all-in-all printers such as the Brother MFC Inkjet and HP LaserJet Pro MFP. These devices act as a combination of copier, fax, printer, and scanner. Multifunctional printers offer convenience to small-firm and home office users, as one can have the full complement of basic office functions in a single machine.

However, such compact-sized multifunctional printers have encountered various problems. For example, the length and width of these machines is determined primarily by paper size (letter-size or A4) rather than technology, making it difficult to reduce their size. Given this situation, manufacturers have made the printing unit ("engine") as small as possible without lowering print quality. Also, since multiple electronic signals (LAN, WiFi, Bluetooth, etc.) can be received simultaneously, signal prioritization is crucial. To cope with this complication, manufacturers have paid special attention to the design of firmware (embedded systems) and software. To achieve complex coordination, communication among teams in charge of firmware, software and various components is critical (based on author interviews with Brother engineers; and on “HP DeskJet 1200C Printer Architecture,” *Hewlett-Packard Journal*, February 1994).

Another example is smartphones such as the iPhone and the Samsung Galaxy. According to Nielsen, in 2016, 207.1 million people in the U.S. used smartphones. The market share was roughly 45% for Apple and 32% for Samsung (http://www.nielsen.com/us/en/insights/news/2016/millennials-are-top-smartphone-users.html). The basic structure of smartphones consists of the application processor, baseband processor, touch screen, camera, wireless communication devices, and battery and power management units. Smartphone designers face two main challenges. The first is supressing noise. Smartphones use high-speed radio communication, which can cause noise and component interference. To minimize these problems, manufacturers have paid especially close attention to circuit design. Most importantly, they have separated the main antenna from the sub-antenna and attempted to achieve low correlation between them (http://www.murata.com/en-global/products/emc/emifil/knowhow/lte/chapter02?intcid5=com_xxx_xxx_cmn_hd_xxx).

Another challenge is maximizing battery life even as high-resolution touch screens and cameras, along with high-speed communication, consume large amounts of power. To resolve this issue, it is critical not only to develop longer-life batteries but also to reduce the power consumption of CPUs, application processors, and other units. This can be achieved through careful coordination among engineers or the teams in charge of different components.[4]

Given these examples, we consider a simple model which assumes that higher architectural integrality decreases a given product’s part-level quality when engineers’ abilities to coordinate design activities are low, but that this disadvantage fades and eventually disappears as engineers’ coordination capabilities improve.[5] Our model then predicts that higher integrality in a product’s architecture raises the product’s overall quality, which derives from system-level quality and part-level quality, when engineers’ coordination capability is relatively high. Conversely, if their coordination capability is relatively low, higher integrality results in lower overall quality. Higher integrality increases the product’s overall quality at the cost of increasing interdependence of

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[4] A classic example of failure of coordination among engineers designing components is Samsung’s Galaxy Note 7. According to a CNBC special report, the Note 7's fatal flaw was caused by a “too aggressive” design policy (http://www.cnbc.com/2016/12/06/samsung-galaxy-note-7-phones-caught-fire-because-of-the-aggressive-battery-design-report.html). To gain an advantage over rival Apple, Samsung tried to squeeze the product to as thin a size as possible. The smaller size, however, brought about a problem. According to the report, the key issue is the battery used in the Note 7. “A smaller battery using standard manufacturing parameters would have solved the explosion issue and the swell issue. But, a smaller battery would have reduced the system's battery life below the level of its predecessor, the Note 5, as well as its biggest competitor, the iPhone 7 Plus.” A potential cause of this defect might be the lack of careful coordination between the battery team and teams in charge of product specifications and testing and refinements.

[5] This assumption is closely related to and consistent with a main finding of Gokpinar, Hopp, and Iravani (2010) as explained in the last paragraph of this section.

component design. When engineers' coordination capability is relatively high, the former (positive) effect outweights the latter (negative) effect so that higher integrality increases the product's overall quality, while the opposite outcomes occurs when their coordination capability is relatively low.

We test this prediction by analysing a unique data set collected by a firm-level survey we administered in Japan, and we find empirical support for our position. Our data set contains information on integrality of product architecture, product quality, and engineers' coordination capability. To our knowledge, ours is the first cross-industry survey that attempts to measure architectural integrality as a continuous variable.

The link between integrality of product architecture and engineers' coordination capabilities is the key element of our analysis. The link between product architecture and organizational characteristics has been studied in the literature. Ulrich (1995) points out relationships between product architecture and organizational issues, including skills and capabilities. He argues that integral architectures may require better coordination and integration skills, whereas modular architectures may require better systems engineering and planning skills (p. 435). Henderson and Clark (1990), drawing on over one hundred interviews with engineers in the photolithographic alignment equipment industry, argue that organizations' knowledge and information-processing structures come to mirror the internal structure of the products they design (p. 27). Given that organizations are slow to change, dominant companies in that industry stumbled in the 1980s when faced with innovations that required radical changes to the product architecture. According to this view, it is organizational characteristics that determine the nature of product architectures and the ways in which they are changed. However, Sanchez and Mahoney (1996) suggest an opposite causal direction. That is, modular product architecture and modular design enable modular organizations. Based on an extensive review of literature dealing with cases from automobile to software, they point out that modular product architectures create information structures that provide the glue that holds together the loosely coupled parts of a modular organizational design.

Several works have recently contributed to our understanding of product architecture by analyzing detailed micro-level data sets. The research focuses on two main issues: the analysis of correlation, and the investigation of performance outcomes.

First, putting forth the "mirroring hypothesis," MacCormack et al. (2012) have explored the correlation between the structure of an organization and the design of the products that the organization produces. Using the design structure matrix data of matched pair software products, they have found the following results: First, while the organizational participants in commercial (or pay) software firms are tightly-coupled with respect to goal, structure, and behaviour, the participants in the open source (or free) software community are loosely-coupled. Second, focusing on software's source file level dependency by counting "function calls" among files, the dependency index of products developed by loosely-coupled organizations is significantly lower (namely, more *modular*) than products from tightly-coupled organizations. Third, even when the functions of products are similar, their product architectures could be different because of the manner in which they mirror different types of organizational structures.[6]

Second, Gokpinar et al. (2010) analyse the impact of the misalignment on quality by studying the vehicle development process of a major auto company and using vehicle quality (warranty repairs) as their performance measure. Based on data from an engineering change order (ECO) system which is used by the firm to manage and document the design process, they create two measures to capture the technological and coordinational relationship among components: (1) the degree of interaction among components and (2) the degree of communicative frequency among engineers. The gap between the two measures is calculated and interpreted as a "coordination deficit." Gokpinar et al.'s (2010) regression results indicate that the coordination deficit is positively associated with quality problems in subsystems.

The novelty of our analysis arises from incorporating the distinction between system-level and part-level qualities in our analytical framework. Gokpinar et al.'s finding is that the greater coordination deficit increases the number of quality problems in subsystems, which means lower part-level qualities. However, warranty repairs involve only part-level quality. From a system-level perspective, fuel efficiency or ride comfort are also important. In the following sections, we derive a new theoretical prediction regarding how architectural integrality affects both part-level and system-level qualities, and we test the prediction empirically.

3. Theoretical Motivation

In this section, we study how the degree of integrality of a product's architecture affects its quality by using a simple model that makes a distinction between system-level and part-level qualities. We posit on a key trade-off that higher integrality in a product's architecture increases its system-level quality at the cost of increasing interdependence of component design, taking into account the engineers' capabilities to coordinate their design activities. A key assumption of the model is that greater architectural integrality results in lower part-level quality when engineers' abilities to coordinate their design activities are low, but that this drawback decreases as engineers' coordination capabilities increase.

Consider the development process of a product that involves multiple engineers (or groups of engineers), where each engineer (or a group of engineers) is assigned to design a component (or a set

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[6] See also Cabigiosu and Camuffo (2012), Furlan, Cabigiosu, and Camuffo (2014), Cabigiosu, Zirpoli, and Camuffo (2013), and Baldwin, MacCormack, and Ransack (2014) for extensions or critiques of this approach.

of components) of the product. Let $x \in [0, \eta]$ denote the integrality of the product's architecture, where $x = 0$ means a completely modular architecture and $x = \eta$ means the highest possible level of integral architecture. Also, let $y \in [0, \lambda]$ denote the level of engineers' capabilities to coordinate their design activities.

The overall quality of the product is determined by its system-level quality and part-level quality. Given the nature of system-level and part-level quality (see Section 1), we assume that system-level quality is determined by x and part-level quality is determined by x and y. Let $G(x)$ and $L(x, y)$, respectively, denote the product's system-level and part-level quality, where both of these functions are continuously differentiable. We assume that overall quality of the product, denoted by $Q(x, y)$, is given by $Q(x, y) = G(x) + L(x, y)$.[7]

Given the nature of system-level and part-level quality, we assume that $G(x)$ and $L(x, y)$ satisfy the following properties. First, $G'(x) > 0$ for all $x \in [0, \eta]$. That is, system-level quality increases as the degree of integrality of the product's architecture increases. Second, $\partial L(x, y) / \partial x < 0$ for all $x \in [0, \eta]$ if $y \in [0, \lambda')$ and $\partial L(x, y) / \partial x = 0$ for all $x \in [0, \eta]$ if $y \in [\lambda', \lambda]$, where λ' ($\in (0, \lambda]$) is a parameter. As x increases, interdependence between designs of different components increases. This makes it difficult for engineers to achieve optimal levels of part-level qualities. We assume that an increase in x reduces part-level quality if engineers' abilities to coordinate their component design is not sufficiently high, whereas, if their coordination abilities are high enough (i.e. $y \in [\lambda', \lambda]$), they can optimally coordinate their design activities even when the degree of integrality is high. We assume $\partial L(x, y) / \partial x = 0$ in this case; that is, part-level quality is unaffected by integrality. Third, $\partial^2 L(x, y) / \partial y \partial x > 0$ for all $x \in [0, \eta]$ and $y \in [0, \lambda')$. As y increases, engineers can better coordinate their design activities, reducing the damage of higher x on part-level quality. Hence, as y increases, an increase in x reduces part-level quality at a decreasing pace. Fourth, we assume that $\partial L(x, 0) / \partial x < - G'(x)$ for all $x \in [0, \eta]$. That is, when engineers' coordination capability is zero, the cost of increasing x on part-level quality is greater than the benefit of increasing x on system-level quality.

The model yields the following result regarding how x affects $Q(x, y)$. There exist values λ^- and λ^+ ($<\lambda'$), $0 < \lambda^- \leq \lambda^+ < \lambda$ such that (i) if $y \in [0, \lambda^-)$, $Q(x, y)$ is strictly decreasing in x for all $x \in [0, \eta]$, and (ii) if $y \in (\lambda^+, \lambda]$, $Q(x, y)$ is strictly increasing in x for all $x \in [0, \eta]$. An increase in x increases system-level quality at the cost of reducing part-level quality as long as $y \in [0, \lambda')$. The result says that the positive effect is dominated by the negative effect when y is relatively small so that total quality is decreasing in x, whereas the reverse is true when y is relatively large. In order to obtain unambiguous results when y is between λ^- and λ^+, we need to make more assumptions regarding second derivatives of functions $G(x)$ and $Q(x, y)$. Here we suppose that $G(x)$ and $Q(x, y)$

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[7] The additive separability is for simplicity and does not affect the qualitative nature of our prediction.

can be approximated as linear functions of x by assuming that $G''(x) = \partial^2 L(x, y) / \partial^2 x = 0$ for all y. The model yields the following prediction.[8]

Testable prediction

Suppose that G(x) and L(x, y) can be approximated by linear functions of x. Then there exists a threshold value y' with (i) and (ii).

(i) If engineers' abilities to coordinate their design activities are lower than the threshold (i.e. if $y < y'$), the product's overall quality is decreasing in the degree of architectural integrality.

(ii) If engineers' abilities to coordinate their design activities are higher than the threshold (i.e. if $y > y'$), the product's overall quality is increasing in the degree of architectural integrality.

4. Empirical Strategy

4.1 Data

To test our prediction, we use a unique data set derived from a firm-level survey that we administered in Japan. The target firms were private-sector firms that belong to the manufacturing and software industries. Firms were chosen from across Japan, with sample firms drawn from the business information database of Tokyo Shoko Research, Ltd. The survey was conducted as a postal survey in March 2010. Details of the number of firms contacted and the number of firms responding are provided in Table 1. The data set contains good proxies for our empirical test, as explained in the next subsection.

Asking all questions to HR managers is a common practice in case studies and questionnaire surveys of this kind. Through a series of discussions with practitioners, however, we came to understand the importance of asking questions related to product architecture to product development managers and questions related to HRM practices to HR managers, Based on this lesson, we have prepared a questionnaire consisting of two sections such that the head of the personnel department first answers the section on the personnel system and HRM practices, and then the head of the product development department answers the section on product development.[9] We believe that this survey method has improved the precision of the information provided by respondents.

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[8] See Appendix for proofs.

[9] The response rate at three percent is extremely low. There are likely two reasons for this. The first is that a considerable number of firms contacted (especially small and medium ones) probably do not have internal product development capabilities and, strictly speaking, should have been screened out. According to the 2008 *Report on the Survey of Research and Development* (Statistics Bureau, 2008), the percentage share of firms that "not only

4.2 Empirical Strategy and Key Variables

In this section, we test our prediction empirically by estimating the following model:

$$q_i = \alpha + \beta_1 x_i + \beta_2 y_i + \beta_3 x_i y_i + Z_i' \gamma + \varepsilon_i,$$

where q_i is the overall quality of the product, x_i is the degree of integrality of the product's architecture, y_i is the level of the engineers' coordination capabilities, and Z_i is the vector of control variables. The key variable of the empirical model is the interaction term between integrality and the engineers' coordination capabilities, $x_i y_i$, which also allows that integrality and the engineers' coordination capabilities independently affect quality. In this empirical model, our prediction translates into $\beta_1 < 0$ and $\beta_3 > 0$. To see this, notice that $\frac{\partial q_i}{\partial x_i} = \beta_1 + \beta_3 y_i$. Then, if $\beta_1 < 0$ and $\beta_3 > 0$, we have that $\frac{\partial q_i}{\partial x_i} < 0$ for all x_i if $y_i < \mathrm{B}$ and $\frac{\partial q_i}{\partial x_i} > 0$ for all x_i if $y_i > \mathrm{B}$, where $\mathrm{B} \equiv -\frac{\beta_1}{\beta_3} > 0$.[10]

In what follows, we explain how we construct key variables in the equations from our data. Regarding the overall quality (q_i), our questionnaire asks the survey respondent's assessment of (i) manufacturing quality and (ii) overall value for customers and their satisfaction with the firm's main product. Each item is measured by an ordered scale from 1 to 10 where 10 represents the cutting edge level of the industry. We use these two variables as proxies for the overall quality, using one variable in one particular regression and the other variable in the other regression, although both regressions have the same explanatory variables.

Next, we move to explanatory variables. A key challenge for our empirical investigation is to measure integrality of product architectures. For this purpose, our questionnaires asked a question based on the idea, derived from Ulrich and Eppinger (2012), that a modular architecture requires relatively more emphasis on the *system-level design* phase of the product development management and less emphasis on the *detailed design* phase than does an integral architecture. Regarding modular architecture, in order to establish a one-to-one mapping between functions and components, careful

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conduct so-called 'research' but also engage in activities aimed at technological improvements and the development of products as well as production and manufacturing processes" was 12.8 percent in the manufacturing sector (11.5 percent for firms with 1-299 employees, 54.0 percent for firms with 300-999 employees, and 81.8 percent for firms with 1,000 or more employees). For the information and communications industry, the overall average was 6.7 percent (6.1% for firms with 1-299 employees, 12.3 percent for firms with 300-999 employees, and 56.7 percent for firms with 1,000 or more employees). The second possible reason is that the questionnaire consisted of two steps, first requiring the head of the personnel department to reply to the section on the personnel system and HR management, and then for the head of the product development department to reply to the section on product development. Due to this complication, it was probably difficult for large firms with several establishments (for example, firms with headquarters in Tokyo but product development in Kyoto) to reply to the questionnaire.

[10] The coefficient β_2 represents the effect of the increase of the engineers' coordination capability on overall quality if product architecture is extremely modular ($x_i = 0$). Our theory does not assume the sign of β_2. Also, our theory does not induce any predictions on the sign of β_2.

planning is required in decomposition of the product into components, which is a key element of system-level design. In contrast, once a one-to-one mapping has been established, specification of the geometry, materials, and tolerance of all of the unique parts in the product, which is a key element of detailed design, is relatively straightforward. Regarding integral architecture, decomposition of the product into components is relatively straightforward because a non-one-to-one mapping between functions and components is allowed. However, a non-one-to-one mapping makes it a more complex and time-consuming task to specify the geometry, materials, and tolerance of the parts in the product.

Hence, the percentage of man-hours spent in the detailed design phase as a share of man-hours spent in the product development process as a whole tends to be higher in integral architecture and lower in modular architecture. In our questionnaire, based on our discussions with several practitioners, we chose "optimizing design parameters" as the keyword to gauge man-hours spent in the detailed design phase. Our choice is consistent with the following insight from Baldwin and Clark (2000): "A "design" is a complete description of an artifact. Designs in turn can be broken down into smaller units, called *design parameters*. For example a red mug and a blue mug differ in terms of the design parameter "color." They may differ in other dimensions as well–for example, height, width, and material." (p.21) Thus, the engineers' core task at the detailed design phase is to optimize the design parameters of the components assigned to them in order to achieve the desired function of the product.

Since most products consist of a number of components, it is not practical to ask the percentage of man-hours spent in the detailed design phase for all components of a product. Our questionnaire asks this percentage only for a product's "key component", which is the most important determinant of the product's quality. Since the key component is likely to have many interfaces with other components of the product, we believe that this percentage for the key component is a reasonable proxy for the product's degree of integrality.

After a series of pre-tests with engineers belonging both to hardware and software companies, we phrased our question as follows:

"*In the development of your main product or information system, what approximately is the percentage of man-hours, as a share of overall development man-hours up until mass production commenced, spent on optimizing the design parameters of the 'key component' in order to achieve the desired function?*"

Answers to this question provide us with information on integrality of product architectures as a continuous variable ranging from 0 to 100. Also, the advantage of this question is its applicability to all industries, including manufacturing and software. We use the natural logarithm of this measure.

Next we explain the variable for engineers’ coordination capabilities (y_i). Our data set contains information that is closely related to two important elements of engineers’ coordination capabilities. The first element is sharing of their knowledge and skills, and the second is effectiveness of their communication. The more knowledge and skills engineers share and the more effectively they communicate with one other, the better they will coordinate design activities.

Firm-sponsored training or in-house skill development is clearly important to optimizing the first element, sharing of knowledge and skills among engineers, since the relevant knowledge and skills are largely firm-specific. Our data set contains information on firm-sponsored training, so we use this information as a proxy for the first element. More specifically, with regard to the development of engineers’ capabilities, our questionnaire asks about the effectiveness of (1) on-the-job training by supervisors; (2) off-the job training within a firm; and (3) experiences with various kinds of product development ranging from 1 to 5, where a larger value means higher effectiveness. We summarize all three measures (ranged from 5 to 15) to produce a composite index and use it as a proxy for the level of engineers’ coordination capabilities. An underlying assumption here is that employers who find higher effectiveness for the three items provide higher levels of firm-specific knowledge and skills through firm-sponsored training and job rotation.

To quantify the second element, effectiveness of communication among engineers, we use the average tenure (in years) of engineers in the firm as a proxy. The underlying idea here is that, if engineers stay in the firm for a longer time, they are more likely to interact with each other and become proficient in firm-specific words and expressions, implying more effective communication. In addition to the aforementioned key variables, we control for product and firm characteristics in the estimation as Z_i.

With regard to product characteristics, we gathered information on the degree of product customization. A firm can enhance the overall quality of its product by designing a product that satisfies specific needs of customers in a certain market segment. Hence the degree of a product’s customization is a key determinant of the product’s overall quality.

Our data set contains variables that measure the ratio of product-specific components and the ratio of firm-specific interfaces, and we use the two variables as proxies for the degree of product customization. Regarding the former, our questionnaire asks the percentage of product-specific components, parts, and elements for the firm’s main products. In the process of designing a customized product, a firm often develops parts and components that are tailored to specific needs of customers in the market segment (i.e., product-specific parts and components), instead of relying on generic and ready-made parts and components. Hence we use this variable as a proxy for the degree of product customization.

Regarding the latter, our questionnaire asks the percentage of firm-specific interfaces (as opposed to generic and ready-made interfaces) for all the key components of the firm's main products. We use this variable as the other proxy for the degree of product customization for two reasons. First, when a product-specific component is connected to another component, the interface between them needs to be a firm-specific one. Hence a higher percentage of firm-specific interfaces implies a higher percentage of product-specific components, leading to a higher degree of product customization. Second, when two generic components are connected to each other, the degree of product customization is higher when they are connected in a unique way by a firm-specific interface rather than in a standard way by a generic interface.

These product characteristics may also be correlated with the coordination capabilities of the engineers who design the product. An engineer designing a product-specific component needs to coordinate his design activity with the activities of engineers in charge of other product-specific components in order to optimize the functionality of his component. Hence a firm that designs a highly customized product is more likely to have engineers with higher coordination capabilities, implying the correlation between the aforementioned two variables and engineers' coordination capabilities. Thus, we need to include these product characteristic variables as control variables in order to address omitted variable bias.

For firm characteristics, we include the number of employees, firm age, sales, and industry fixed effects (machinery, non-machinery, and software industries). Summary statistics of the above variables are presented in Table 2. Using these variables, we estimate the estimation equation by OLS.[11]

5. Empirical Results

The OLS results are shown in Table 3. Column (1) shows the result that uses manufacturing quality as a measure of product development and the HR development index as a measure of the engineers' coordination capability. The coefficient for the log of integrality, β_1, is negative and statistically significant at conventional levels. That implies that, given the engineers' low coordination capability, the increase of the integrality undermines the outcome of product development. This supports our first theoretical prediction. In addition, the coefficient of the interaction term between the log of degree of integrality and HR development, β_3, is positively significant. This suggests that the

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[11] Our dependent variable is measured by ordered scale from 1 to 10. We also estimate the equation by ordered probit. We confirm that all the results by ordered probit are qualitatively similar to those by OLS. See Table 4.

the increase of the integrality with the increase in coordination capability improves the outcome of the product development. These coefficients suggest that the threshold value of engineers' coordination capability B $\equiv -\frac{\beta_1}{\beta_3}$ is 12.57 and is within the domain of the variable (from 1 to 15). That is, the increased integrality enhances the product development performance in the range of the coordination capability above 12.57. About 70% of our observations assign higher values to the variable than to the threshold value. This result supports the second part of our second theoretical hypothesis. Thus, the estimation results support both parts of our theoretical prediction.

Note that the coefficient for HR development practices, β_2, is negatively significant. This implies that improvement in HR development practices results in decreased product performance when the log of degree of integrality is zero. When considering the interaction effect, β_3, the threshold value of log of degree of integrality B' $\equiv -\frac{\beta_2}{\beta_3}$ is 3.11. Only 30% of our observations have a lower value for the variable than for the threshold value. Our result suggests that improved HR development?> would have negative effects when firms develop highly modular (less integral) products. The increase of HR development does not always work positively.

Figure 1 visualizes our estimation results in column (1) in Table 3. Both Figures 1 (a) and (b) depict the relationship between the degree of integrality (horizontal axis) and manufacturing quality (vertical axis). Figure 1 (a) represents the relationship between the degree of integrality and manufacturing quality, fixing engineers' coordination capability measured by HR development practices in the lower spectrum (assuming the value is at a 5 percentile). Figure 1 (b) represents the same relationship, fixing engineers' coordination capability in the higher spectrum (assuming the value is at a 95 percentile). Given lower engineers' coordination capability, the increase of the degree of integrality is associated with a counter-productive outcome: it reduces product quality. On the other hand, given higher engineers' coordination capability, the increased integrality enhances the product quality. This result closely matches our hypothesized outcome.

To check the robustness of the choice of performance variable, we use customer satisfaction as a measure of product development performance. Column (2) in Table 3 shows the result. The results are quite similar to the results in column (1) both in statistical significance and the magnitudes of coefficients. Our theoretical prediction is robust in the choice of measure of development performance.

We also check the robustness of the choice of the measure of engineers' coordination capability. Engineers' average tenure years is used to measure this capability. Results are shown in column (3) of Table 3. Similar to the results that uses HR development practices, the coefficient for the log of integrality is negatively significant, and the coefficient for the interaction term between log of architecture and log of average tenure years is positively significant. If we use customer satisfaction as a measure of the performance of product development, we obtain similar results (column (4) of Table 3).

Furthermore, we include both proxies for engineers' coordination capability in the regression at the same time to fully capture the effect. Results are shown in column (5) of Table 3. The magnitude of each parameter is slightly changed. The sign and significance, however, are unchanged. The coefficient for the log of architecture is still negatively significant, and interaction terms to both proxies (HR development practices and log of average tenure years) are positively significant. Column (6) of Table 3 shows the result when we use customer satisfaction as a measure of the performance of product development. However, on coefficients for interaction terms, only the coefficient for the interaction term between HR development and log of architecture is significant. The coefficient for the interaction term between log of average tenure years and log of architecture becomes insignificant, but the coefficient is still positive. In sum, even including both measures of engineers' coordination capability, our testable prediction is still supported.

The overall qualities are measured by ordered scale. For this reason, we estimate the equation by ordered probit. The results are shown in Table 4. Results are qualitatively similar to the OLS. The coefficients for log of the degree of integrality are negatively significant, and those for interaction terms are positively significant in the specifications using both manufacturing quality and customer satisfaction as performance variables, and HR development practices and log of average tenure years as the measure of engineers' coordination capability. One important difference to the OLS results is shown in column (6) of Table 4. In the ordered probit estimation, interaction terms between log of architecture and both proxies (HR development practices and log of average tenure years) are positively significant. In sum, the two theoretical predictions are robustly supported by the statistical tests, regardless of the choice of explanatory variables and estimation procedure.

6. Conclusion and Managerial Implication

How does the integrality of a product's architecture affect quality of the product? To address this question, we make a distinction between system-level and part-level quality and posit that there exists a key trade-off in which a greater degree of integrality in a product's architecture increases its system-level quality but is likely to entail the drawback of increasing interdependence in component design, taking account of the engineers' abilities to coordinate their design activities. Consistent with Gokpinar et al.'s (2010) finding that a higher large coordination deficit increases the number of quality problems in subsystems, our model assumes that higher architectural integrality decreases part-level quality when engineeers' coordination capabilities are inadequate. Greater integrality increases the product's system-level quality but will probably result in the undesired situation of increased interdependence in component design. We hypothesize that, when engineers' coordination capability is relatively high, the former (positive) effect outweighs the latter (negative) effect so that greater integrality increases the product's overall quality, but that the opposite outcome will occur when their coordination capability is relatively low. We find empirical support for this hypothesis by analysing a set of unique data that are derived from a firm-level survey we administered in Japan.

Our analysis yields an important implication for managers making strategic decisions regarding product design. That is, firms should take into account the link between product architecture and organizational coordination when they position their products in the market. A product's architectural integrality should be closely linked to the nature of the market segment at which the product is targeted. If a firm decides to design a product that is targeted to consumers who require higher system-level quality, the firm can meet the requirement by choosing high architectural integrality for the product. When making such a decision, however, the firm should carefully investigate its engineers' capability to coordinate design activities, because higher architectural integrality may reduce the product's part-level quality if their coordination capability is inadequate. In such a case, the firm may need to make significant investments to improve their coordination capability, which may in turn imply that the firm cannot profitably target the envisioned market segment. The firm may then be better off by targeting another segment that can be served with lower system-level quality.

With regard to organizational coordination, this paper has focused on intra-firm coordination between engineers within a firm. However, inter-firm coordination between engineers in multiple firms is also important when we consider firms' strategic decisions about product design, because firms often outsource some of their design activities. In future research, we plan to analyse the link between product architecture and organizational coordination by explicitly incorporating inter-firm coordination and outsourcing of design activities in our analytical framework.

Appendix

This appendix presents proofs for the results mentioned in Section 3.

We posit that $\partial Q(x, y)/\partial x = G'(x) + \partial L(x, y)/\partial x$, and, hence, the first, the second, and the fourth assumptions together imply that $\partial Q(x, 0)/\partial x < 0$ and $\partial Q(x, \lambda)/\partial x > 0$ for all $x \in [0, \eta]$. Then, since both $G(x)$ and $L(x, y)$ are assumed to be continuously differentiable functions, there exist values λ^- and λ^+ ($< \lambda'$), $0 < \lambda^- \leq \lambda^+ < \lambda$ such that (i) if $y \in [0, \lambda^-)$, $\partial Q(x, 0)/\partial x < 0$ for all $x \in [0, \eta]$, and (ii) if $y \in (\lambda^+, \lambda)$, $\partial Q(x, 0)/\partial x > 0$ for all $x \in [0, \eta]$.

Next suppose that $G''(x) = \partial^2 L(x, y) / \partial^2 x = 0$ for all $y \in [0, \lambda']$. The third assumption then implies that there exists a value $y' \in (0, \lambda')$ such that $\partial Q(x, y)/\partial x < (=, >) 0$ for all $x \in [0, \eta]$ if $y < (=, >) y'$.

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Table 1. Details of questionnaire surveys

		Population	No. of responses	Response rate
Total		3,504	104	3.0%
No. of employees	Fewer than 300	1,345	50	3.7%
	300-499	882	24	2.7%
	500-999	666	18	2.7%
	1,000 or more	611	12	2.0%
Industry	Manufacturing	3,115	89	2.9%
	Machinery	1,353	44	3.3%
	Other than machinery	1,762	45	2.6%
	Software industry	389	15	3.9%

Notes: 1. Sample firms were drawn from the business information database of Tokyo Shoko Research, Ltd.

2. Firms with 185 or more employees only.

Table 2. Summary statistics

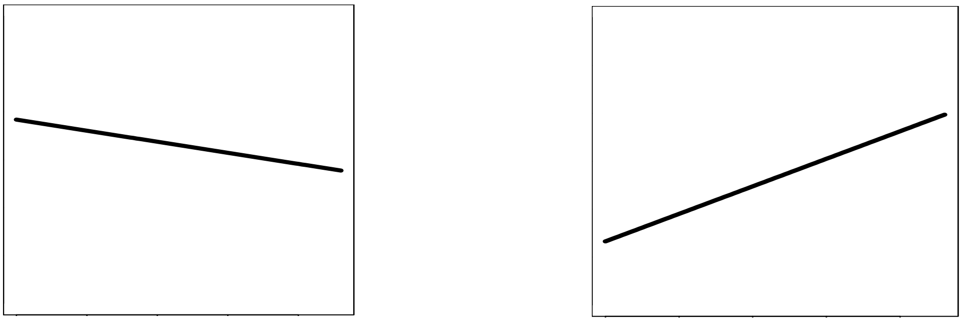
Variable	Obs	Mean	SD	Min	Max
Manufacturing quality	62	7.693548	1.337832	3	10
Consumer satisfaction	62	7.403226	1.396244	3	10
Degree of integrality	62	40.96774	22.75743	5	90
Average tenure years	62	12.76129	4.392182	6	25.5
HR development practices	62	13.06452	1.19933	9	15
No. of workers	62	6.02607	0.946964	4.941642	10.16196
Age	62	3.922087	0.3113013	3.218876	4.574711
Sales	62	7.584925	2.3445	2.302585	13.91082
Share of product specific parts	62	47.37097	31.59697	2	100
Openness of product interfaces	62	54.35484	28.27679	10	100
Machinery industry	62	0.4354839	0.4998678	0	1
Non-machinery industry	62	0.4032258	0.4945499	0	1

Table 3. Baseline results

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable: Overall qualities	Manufacturing quality	Consumer satisfaction	Manufacturing Quality	Consumer satisfaction	Manufacturing Quality	Consumer satisfaction
ln(Degree of integrality)	-5.067**	-5.152**	-3.473***	-3.667***	-6.140***	-6.041***
	(-2.185)	(-2.290)	(-2.747)	(-2.717)	(1.628)	(1.761)
HR development practices	-1.256**	-1.165*			-0.856*	-0.648
	(-2.073)	(-1.961)			(0.467)	(0.668)
ln(Degree of integrality)×HR development practices	0.403**	0.399**			0.288**	0.249
	(2.299)	(2.292)			(0.141)	(0.193)
ln(Average tenure years)			-5.347***	-4.831**	-4.114***	-3.792
			(-3.278)	(-2.316)	(1.316)	(2.367)
ln(Degree of integrality) × ln(Average tenure years)			1.494***	1.508**	1.072**	1.151*
			(3.035)	(2.663)	(0.430)	(0.669)
ln(No. of workers)	-0.377	-0.229	-0.269	-0.146	-0.287	-0.197
	(-1.451)	(-0.920)	(-0.983)	(-0.575)	(0.269)	(0.255)
ln(Age)	1.004	-0.128	0.491	-1.736	1.331	-0.998
	(0.711)	(-0.0812)	(0.329)	(-0.694)	(1.497)	(2.361)
ln(Sales)	0.107	0.0536	0.0892	0.0365	0.0950	0.0422
	(0.944)	(0.532)	(0.789)	(0.366)	(0.117)	(0.101)
ln(Share of product specific parts)	0.210	-0.0120	0.217	0.00616	0.188	-0.0438
	(1.064)	(-0.0580)	(0.872)	(0.0233)	(0.211)	(0.215)
ln(Openness of product interfaces)	-0.180	0.164	-0.263	0.130	-0.260	0.139
	(-0.785)	(0.528)	(-1.155)	(0.431)	(0.227)	(0.307)
Machinery industry	0.437	0.257	0.526	0.317	0.458	0.284
	(0.699)	(0.422)	(0.923)	(0.587)	(0.612)	(0.587)
Non-machinery industry	-0.0859	0.224	0.0516	0.374	-0.0258	0.384
	(-0.138)	(0.371)	(0.0921)	(0.665)	(0.591)	(0.577)
Constant	20.91**	22.97**	19.23**	25.16**	24.31***	28.76***
	(2.363)	(2.415)	(2.554)	(2.483)	(6.266)	(9.163)
Observations	62	62	62	62	62	62
R-squared	0.225	0.105	0.238	0.100	0.275	0.141

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Figure 1. Relationships between architecture and manufacturing quality



(a) Low coordination capability case

(b) High coordination capability case

Table 4. Results by ordered probit

Dependent variable: Overall qualities	(1) Manufactruing quality	(2) Customer satisfaction	(3) Manufactruing quality	(4) Customer satisfaction	(5) Manufactruing quality	(6) Customer satisfaction
ln(Degree of integrality)	-5.645**	-5.711***	-4.339***	-4.242***	-8.198***	-7.951***
	(2.454)	(2.157)	(1.459)	(1.480)	(2.021)	(2.272)
HR development practices	-1.518**	-1.370**			-1.273***	-1.043*
	(0.666)	(0.577)			(0.482)	(0.558)
ln(Degree of integrality) x HR development	0.449**	0.437***			0.377***	0.341**
	(0.186)	(0.165)			(0.138)	(0.156)
ln(Average tenure years)			-6.784***	-5.501***	-5.761***	-4.746***
			(1.895)	(2.033)	(1.441)	(1.813)
ln(Degree of integrality) x ln(Average tenure years)			1.842***	1.692***	1.463***	1.409***
			(0.559)	(0.589)	(0.450)	(0.542)
ln(No. of workers)	-0.232	-0.214	-0.137	-0.148	-0.109	-0.173
	(0.198)	(0.183)	(0.202)	(0.177)	(0.199)	(0.180)
ln(Age)	0.941	-0.257	0.793	-1.824	1.763	-1.137
	(1.359)	(1.296)	(1.616)	(2.104)	(1.662)	(2.024)
ln(Sales)	0.0991	0.0586	0.0822	0.0372	0.0915	0.0470
	(0.0880)	(0.0730)	(0.0896)	(0.0713)	(0.0934)	(0.0728)
ln(Share of product specific parts)	0.172	-0.0690	0.152	-0.0765	0.151	-0.121
	(0.148)	(0.154)	(0.173)	(0.185)	(0.167)	(0.169)
ln(Openness of product interfaces)	-0.111	0.161	-0.231	0.120	-0.236	0.146
	(0.198)	(0.225)	(0.194)	(0.224)	(0.196)	(0.227)
Machinery industry	0.479	0.175	0.634	0.272	0.539	0.212
	(0.422)	(0.413)	(0.415)	(0.369)	(0.421)	(0.389)
Non-machinery industry	-0.0685	0.242	0.173	0.493	-0.0107	0.446
	(0.440)	(0.426)	(0.419)	(0.423)	(0.422)	(0.407)
Estimation	Probit	Probit	Probit	Probit	Probit	Probit
Observations	62	62	62	62	62	62
Log Likelihood	-83.25	-99.09	-80.89	-98.67	-78.92	-96.57

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1