Choice of Product Architecture, Product Quality, and Intra-Firm Coordination: Theory and Evidence

by

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Abstract

Product development is an important element of value-creating activities, and the choice of product architecture plays a critical role in the product development process. The term product architecture is typically understood to refer to the way products as a system are divided into subsystems and how the interfaces among these subsystems are defined. The objective of our paper is to study interconnections among the firm's choice of integrality of product architecture, consumers' preferences for product quality, and engineers' capabilities to coordinate their product-design activities.

In the theoretical part of the paper, we consider a firm that chooses integrality of its product's architecture. The firm also chooses the level of its investment in enhancing its engineers' capabilities to coordinate their design activities. Our model predicts that, as consumers' valuation for product quality increases, the firm invests more in engineers' coordination capabilities. Higher coordination capabilities increase product quality through two channels. They have positive direct effects on the product's local qualities. At the same time, higher coordination capabilities raise the optimal integrality of the product's architecture, and this in turn increases the product's global qualities. We investigate this prediction by analysing data we collected through administration of questionnaire surveys to manufacturing and software companies in Japan, Korea, and China. We test our prediction by the two-stage least squares procedure, and find empirical supports in Japan and China but not in Korea. We discuss possible reasons for the lack of empirical support in Korea.

1. Introduction

Product development (or product design) is an important element of value-creating activities[1], and the choice of product architecture plays a critical role in the product development process. The seminal paper by Ulrich (1995) generated burgeoning interests in the role of product architecture, resulting in a growing body of research focusing on this concept. The term product architecture is typically understood to refer to the way products as a system are divided into subsystems and how the interfaces among these subsystems are defined (see, e.g., Baldwin and Clark, 2000; Fujimoto, 2001).

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). Also, components connected by an interface are relatively independent between each other in the sense that a change made to the design of a component does not require many changes to the design of other components. In contrast, in an integral architecture, mapping between functions and components are more complex (non one-to-one) and the designs of components connected by interfaces are highly dependent between each other (Ulrich, 1995; Fujimoto, 2001). Integrality and modularity are relative properties of product architecture. Products are rarely strictly modular or integral. Rather, we can say that they exhibit either more or less integrality/ modularity than a comparative product (Ulrich and Eppinger, 2011).

The objective of our paper is to study interconnections among the firm's choice of integrality of product architecture, consumers' preferences for product quality, and engineers' capabilities to coordinate their product-design activities. Development of complex products involves multiple persons (see, for example, Baldwin and Clark, 2000). 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. Engineers' capabilities to coordinate their activities become more important as integrality of the product's architecture increases, because the design of different components are highly dependent among each other under an integral architecture.

[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).

What is the trade-off associated with the choice of integrality of product architecture? Below we will provide an explanation for the trade-off through use of a simple stylized example. Let us consider a product that performs three functions, denoted by 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 (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 component does not affect the design of other components. In this way, component-function matching is easy under modular architecture.

The size of the product can be reduced by increasing integrarity of 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, because they jointly perform function B. The other strategy is geometry nesting, in which components are placed in smaller physical space. The shape of one component would then be affected by the shapes of some other components because they have to be put in a limited physical space, creating interdependence of the component design.

We can describe the trade-off in general terms, using concepts of *global qualities* and *local qualities*. Following Ulrich (1995, p. 432), define local qualities as qualities that arise only from the properties of a local region of the product, and global qualities as qualities that arise from the physical properties of most, if not all, of the components of the product.[2] The overall quality of the product consists of global qualities and local qualities. In the aforementioned example, the product's qualities associated with functions A, B, and C are local qualities, and the size of the product is a global quality.

Global qualities of a product can be raised by increasing integrality of the product's architecture. Higher integrality, however, increases interdependence between designs of different components, making it difficult for engineers to coordinate their design activities to optimize the product's local qualities. In the theoretical part of the paper, we analyse a simple model that captures this trade-off. The model considers a firm that chooses integrality of its

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

product's architecture. The firm also chooses the level of its investment in enhancing its engineers' capabilities to coordinate their design activities. We find that, as consumers' valuation for product quality increases, the firm invests more in engineers' coordination capabilities. Higher coordination capabilities increase product quality through two channels. They have positive direct effects on the product's local qualities. At the same time, higher coordination capabilities raise the optimal integrality of the product's architecture, and this in turn increases the product's global qualities.

Our theoretical analysis therefore yields the following testable prediction: As consumers' valuation of product quality increases, the firm's investment in engineers' coordination capability increases. Higher coordination capabilities, in turn, increases the integrality of product architecture. We investigate this prediction empirically by analysing data we collected through administration of questionnaires to manufacturing and software companies in Japan, Korea, and China.[3]

A challenge of our empirical investigation is to measure integrality of product architectures. For this purpose, our questionnaires asked a question based on the idea that a modular architecture requires relatively more emphasis on *system-level design* phase of the product development management and less emphasis on *detailed design* phase than does an integral architecture. This idea, due to Ulrich (1995), can be explained as follows.

The product development process can be viewed as consisting of four phases: concept development, system-level design, detailed design, and product testing and refinement. Under a modular architecture, interfaces between components and a set of functions to be performed by each component are carefully defined in the system-level design phase. The modular architecture then puts less emphasis on the detailed design phase than does the integral architecture, because, once the system-level design is completed, detailed design of each component can proceed almost independently and in parallel. In contrast, under an integral architecture, a product is divided into a relatively small number of subsystems in the system-level design phase. These subsystems are then assigned to multi-disciplinary teams who will share the responsibility for designing components that make up the subsystem in the detailed design phase. The integral architecture puts more emphasis on the detailed design phase than does the modular architecture, because component designers interact continually in order to

[3] The primary objective of the data collection had not been this paper but several other research projects related to this paper. As such, questions asked in our questionnaires are not necessarily perfect match with information most desirable for the empirical test of this paper.

analyse performance of the subsystem to which their component belongs and to manage changes required because of component interaction.

In our questionnaires, we ask 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, and use the percentage as a measure of integrality of the product's architecture (a larger percentage implies higher integrality). Based on our discussions with several engineers, we have chosen "design parameters" as the keyword to ask man-hours spent in the detailed design phase. According to Boldwin 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."

Engineers' tasks at the detailed design phase are to optimize the design parameters of the components assigned to them in order to achieve the desired function of the product. We have 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 integrarity of product architectures as a continuous variable ranging from 0 to 100.

Our data set do not contain a direct measure of engineers' abilities to coordinate their activities. However it contains average tenure years of the engineers, and we use this information as a proxy for engineers' retention rate. Our theoretical model links engineers' capabilities to coordinate their activities to their retention rate, based on the idea that the longer the engineers work together the better they can coordinate their activities. See Section 5 on how we measure consumers' valuation of product quality.

We test our theoretical prediction by the two-stage least squares (2SLS) procedure, where our theoretical prediction is interpreted as follows. First, consumers' valuation of product quality determines engineers' retention rate. We test this in the first-stage estimation, where a positive coefficient for consumers' valuation (which is an exogenous explanatory variable) supports our prediction. Next, as the predicted retention rate determined by the first-stage equation increases, the firm increases the integrality of product architecture. We test this in the second-stage estimation, where a positive coefficient for the predicted retention rate supports our prediction.[4]

We find empirical support for our prediction for the Japanese and Chinese cases, but not for the Korean case. Section 6 presents a discussion on a possible reason for the lack of support in the Korean data.

In the remainder of the introduction, we discuss our paper's contributions to related literatures. What are the determinants of product architecture? We contribute to the product development / design literature by exploring this research question from new perspectives. Most previous studies are based on the idea that the nature of product architecture is determined by the nature of the product. Changes in product architecture have been studied as firms' responses to changes in exogenous factors such as underlying technologies, functional requirements of consumers, and the stages of product life-cycle (see, for example, Henderson and Clark, 1990; Kusunoki and Chesbrough, 2001). However, firms may strategically choose architecture of their products, as pointed out, for example, by Fujimoto (2001). Tsuru and Morishima (2011) hypothesized that firms strategically choose their product architecture, and presented evidences that support this hypothesis from their case studies in Japan, Korea, and China, focusing on firms making the same products (cellular phones, liquid crystal televisions, and business information systems).

We contribute to the literature by analysing firms' strategic choices of product architecture both theoretically and empirically. Equally important, we study the link between a firm's strategic choice of product architecture and its engineers' abilities to coordinate their activities, where the latter is captured by engineers' retention rate in our analyses. Several papers have previously studied the link between product architecture and organizational capabilities (see, for example, …). Complementary to these earlier contributions, our analysis suggests an important link between choice of product architecture and human resource management strategy for engineers.

[4] In the estimation, because our data do not contain engineers' turnover rate, we use normalized average tenure years of the engineers as an inverse proxy for the turnover rate. Thus, we consider the coefficient inversely, and the positive coefficients in both stages are consistent with our theoretical prediction.

Regarding empirical measure of product architecture, most previous studies were based on the dichotomy of integral or modular architecture, and directly asked in their questionnaires whether a product in question adopts integral or modular architecture. In contrast, as mentioned above, we have devised more objective way to measure integrality of product architecture as a continuous variable. Our empirical analysis is based on questionnaires to manufacturing and software companies in Japan, Korea, and China. Previous studies on international comparisons of product architecture, based mainly on case study methods, have pointed out a typology that Japanese firms tend to adopt integral architecture to produce high quality products, whereas Chinese firms tend to adopt modular architecture to produce standardized products (see, for example, Fujimoto (2001); Fujimoto and Shintaku(2005)). Furthermore, to our knowledge, little previous research has studied the choice of product architecture in Korea. We therefore believe that it is meaningful to undertake comprehensive questionnaire surveys on choice of product architecture and related issues in the three largest economies in East Asia.

Coordination within an organization has been recognized as an issue of central importance in the organizational economics literature (see, for example, Milgrom and Roberts (1992) and Roberts (2004)). Alonso, Dessein and Matouschek (2008) and Rantakari (2008) have recently considered theoretical models of multi-divisional organization in which decisions must be adapted to local conditions but also coordinated with each other. They analysed their models to study how the allocation of decision rights within an organizational hierarchy influences a trade-off between coordination and adaptation.

We contribute to the literature by exploring a simple model in which the degree of interdependence is endogenously determined. An increase in integrality of a product's architecture increases the product's global qualities. This benefit, however, comes with the cost of increasing interdependence between designs of different components. This trade-off determines the optimal degree of the interdependence in our model.

The degree of interdependence between actions taken by different divisions or individuals is exogenously given in existing analyses of intra-firm coordination, with Rantakari (2011) as a notable exception. Rantakari (2011) put forth a model in which the importance of inter-divisional coordination (called the level of "operational integration") is a choice variable and endogenously determined through the following trade-off: An increase in the level of operational integration in itself increases the firm's profit. However, it also increases the damage of incomplete inter-divisional coordination on the firm's profit. Rantakari's model and ours are related but different, because it is interdependence itself, rather than its importance, that is endogenized in our analysis. Rantakari theoretically analyses the joint determination of the level of operational integration, the allocation of decision rights, and the compensation structure of its managers. We focus on the link between a firm's choice of product architecture and its engineers abilities to coordinate their activities, and empirically explore our theoretical predictions.

The rest of the paper proceeds as follows. Section 2 formulates our model, and Section 3 analyzes the model and derives the testable prediction. Section 4 explains the nature of the survey methodology and the nature of the data. Sections 5 and 6 outline the empirical strategy and present the results regarding the prediction. Section 7 summarizes the main results and outlines implications of the results.

2. The Model

Consider a firm that designs and sells a product which consists of two components, 1 and 2. The firm has two engineers, 1 and 2. Engineer i (= 1, 2) is in charge of the design of component i, and chooses an action $a_i (\in \Re)$, which is an important determinant of local quality associated with component i. Let q denote the level of overall quality of the firm's product. We assume that q is given by:

(1) $$q = R + kx - (a_1 + xa_2 - \theta_1)^2 - (a_2 + xa_1 - \theta_2)^2,$$

where $R + kx \equiv G(x)$ represents the product's global quality and $-(a_i + xa_j - \theta_i)^2 \equiv L_i(a_i, a_j)$ (i, j = 1, 2, $i \neq j$) represents its local quality associated with component i.

The nature of the product's architecture is denoted by $x \in [0, \eta]$ $(0 < \eta < 1)$, where $x = 0$ represents modular architecture and $x = \eta$ represents the most integral architecture possible. As x increases, integrality of the product's architecture increases. The firm chooses x to maximize its expected profit.

The trade-off concerning integrality of product architecture is captured as follows. By choosing $x = \eta$, the firm can maximize the product's global quality $G(x) = R + kx$, where R (> 0) represents the level of global quality under modular architecture and k (> 0) represents the increment of global quality as integrality of architecture increases. An increase in integrality, however, increases the degree of interaction between the two components when they are designed. In our model, local quality associated with component i, $L_i(a_i, a_j) = -(a_i + xa_j - \theta_i)^2$, is determined not only by engineer i's action a_i but also by engineer j's action a_j. The effect of engineer j's action on the local quality of component i is nil when x = 0, and it increases as the integrality of architecture x increases.

Each engineer i chooses a_i to maximize the expected value of component i's local quality $L_i(a_i, a_j) = -(a_i + xa_j - \theta_i)^2$, after having observed the realization of a random variable θ_i that represents the local conditions faced by engineer i. We assume that θ_i is identically and independently distributed according to a known distribution with an expected value $E(\theta)$ and a variance $Var(\theta)$.

Each engineer i can also observe the realization of the other engineer's local conditions, θ_j, if both engineers have worked for the firm for a sufficiently long period of time. We incorporate this idea into our model in a reduced form by assuming that both engineers work for the firm for a sufficiently long period of time with probability 1 – t ($t \in (0, 1)$) and we interpret t as the engineers' turnover rate. We assume that the turnover rate t is given by $t = T - y$, where $T > 0$ is a given constant and $y \in [0, T]$ is the level of investment made by the firm to reduce t. The cost of the investment is a convex function c(y), and we let c(y) = to obtain closed-form solutions in the analysis.

On the demand side, there is a measure one of identical consumers whose gross benefit from consuming one unit of the firm's product with quality q is Vq, where V > 0 is a parameter. Each consumer consumes at most one unit of the firm's product. Once a product with quality q is developed, the firm can produce the product at zero marginal cost. Then the firm sells the product with quality q at the price of Vq to all consumers.

We consider the following three-stage game:

Stage 1 [Choice of product architecture and investment in reducing engineers' turnover]:
The firm chooses (x, y) to maximize its expected profit. The choice becomes common knowledge.

Stage 2 [Turnover]:
Uncertainty regarding engineers' turnover is settled and becomes common knowledge.

- Both engineers remain with the firm with probability 1 – t.
- At least one engineer turns over and is replaced by a new one with probability t.

Stage 3 [Engineers' actions]:
Both θ_1 and θ_2 realize, and each engineer i chooses a_i to maximize the expected value of component i's local quality $L_i(a_i, a_j) = -(a_i + xa_j - \theta_i)^2$.

- Each engineer i can observe both θ_i and θ_j if both engineers have remained with the firm.
- Each engineer i can observe θ_i only, otherwise.

Then the firm's product quality q is realized, the firm sells the product at a price of Vq to all consumers, and the game ends.

3. Analysis of the Model

We derive Subgame Perfect Nash Equilibria (SPNE) in pure strategies of the model. Proofs of propositions are presented in the Appendix. Let x* and y*, respectively, denote the values of x and y the firm chooses at stage 1 in equilibrium. We say that the equilibrium is an interior equilibrium if $x^* \in (0, \eta)$ and $y^* \in (0, T)$ hold. We make the following assumption, which is a necessary and sufficient condition for the equilibrium turnover rate to be strictly positive for any given $x \in [0, \eta]$:

Assumption 1: $\eta < \sqrt{\frac{T}{2VB}}$,

where $B \equiv \mathrm{Var}(\theta)$.

Every stage 3 subgame can be represented by (x, y) and whether or not turnover occurred at stage 2. Let us first consider stage 3 subgames in which turnover did not occur at stage 2, which we call no-turnover subgames. In this case, having observed both θ_i and θ_j, each engineer i correctly anticipates engineer j's action a_j and chooses a_i to achieve the maximum possible level of the local quality $L_i(a_i, a_j)$, which is zero in the equilibrium of no-turnover subgames. Then the equilibrium quality level is given by $q_{no\text{-}turnover}=G(x) = R + kx$.

Next consider stage 3 subgames in which turnover occurred at stage 2, which we call turnover subgames. We find that the expected quality level in the equilibrium of a turnover subgame is $q_{turnover} = R + kx - 2x^2\mathrm{Var}(\theta)$, which is below $q_{no\text{-}turnover}$ because each engineer i cannot observe θ_j and hence cannot correctly anticipate a_j in turnover subgames. The difference between $q_{no\text{-}turnover}$ and $q_{turnover}$, $2x^2\mathrm{Var}(\theta)$ increases as the integrality of product architecture x increases and as the variance of the local condition $\mathrm{Var}(\theta)$ increases.

Let q*(x, y) denote the expected quality level in the equilibrium of the stage 1 subgame represented by (x, y). We have that q*(x, y) is given by:

(2) $q^*(x, y) = tq_{turnover} + (1 - t)q_{no\text{-}turnover} = R + kx - 2tx^2Var(\theta)$.

At stage 1, the firm chooses (x, y) to maximize its expected overall profit in the subsequent equilibrium, which is denoted π(x, y) and given by:

(3) $\pi(x, y) = Vq^*(x, y) - c(y) = V[R + kx - 2tx^2Var(\theta)] - \frac{1}{2}y^2$.

Proposition 1 [Equilibrium characterization]

There exists a unique value K > 0 such that the game has a unique equilibrium outcome (except possibly when k = K) with the following properties:[5]

(i) If k = 0, $x^* = y^* = 0$ holds.

(ii) If 0 < k < K, $x^* \in (0, \eta)$ and $y^* = 2VVar(\theta)(x^*)^2$ hold, where x* is strictly increasing in k.

(iii) If k > K, $x^* = \eta$ and $y^* = 2VVar(\theta)\eta^2$ hold.

The logic behind Proposition 1 can be explained as follows. Recall that an increase in x means an increase in the integrality of product architecture. An increase in integrality increases its global quality G(x) = R + kx, but increases the degree of interaction between the two components in their determination of local qualities. When k = 0, product integrality has no effect on its global quality, and so the firm chooses x = 0 (modular architecture) to eliminate component interactions. As k increases, an increase in product integrality increases its global quality more effectively, and hence the firm chooses more integral architecture in the equilibrium (that is, x* is increasing in k). When k becomes large enough, the firm chooses the most integral architecture (x = η), and any further increase in k has no effects on the equilibrium integrality.

Let us now turn to the comparative statics exercise in terms of V, which is a parameter that captures consumers' valuation of product quality.

Proposition 2 [Comparative statics]

Suppose that 0 < k < K holds so that the game has a unique interior equilibrium. We then have that both x* and y* are strictly increasing in V.

[5]Suppose k = K. The game has a unique equilibrium outcome $x^* \in (0, \eta)$ and $y^* = 2VVar(\theta)(x^*)^2$ if $\eta \leq \sqrt{\frac{T}{6VB}}$, whereas the game has two equilibrium outcomes ($x^* \in (0, \eta)$ and $y^* = 2VVar(\theta)(x^*)^2$ in one equilibrium and $x^* = \eta$ and $y^* = 2VVar(\theta)\eta^2$ in the other) otherwise.

Pick any k satisfying $k \in (0, K)$, so that the corresponding equilibrium outcome (x^*, y^*) is interior. Since the equilibrium integrality x^* is strictly positive, the equilibrium quality in the event of engineers' turnover, $R + kx^* - 2(x^*)^2\mathrm{Var}(\theta)$, is strictly lower than the equilibrium quality in the event of no turnover, $R + kx^*$. The firm can then increase its expected product quality by investing more in y to reduce the turnover rate t. An increase in V means an increase in consumers' willingness to pay for product quality. Hence, as V increases, the firm's marginal revenue from increasing its expected product quality increases, implying that the firm invests more in y to reduce t. The lower turnover, in turn, induces the firm to increase the integrality of its product architecture. This is because higher integrality increases the product's global quality at the expense of lower local quality in the event of engineers' turnover, and so the lower turnover rate decreases the firm's disadvantage associated with higher product integrality. Higher integrality, in turn, induces the firm to further reduce engineers' turnover by investing more in y. The result is that an increase in V increases both x^* and y^*.

Proposition 2 and the logic behind the proposition described above together imply that our theoretical analysis yields the following testable prediction regarding interconnections among consumers' valuation of product quality, engineers' turnover, and integrality of product architecture. We will investigate this prediction empirically in the next sections.

Testable prediction

As consumers' valuation of product quality increases, engineers' turnover rate decreases. A lower turnover rate, in turn, increases the integrality of product architecture.

4. Description of the Data

We administered a firm-level survey in Japan, Korea, and China. The survey questionnaire was identical for all three countries, and the actual survey was conducted after a pretest.

The target firms in Japan were private-sector firms belonging to the manufacturing and software industries and with 185 or more employees. 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(a).

Target firms in Korea consisted of private-sector firms in the manufacturing industry (with 300 or more employees) and the software industry (with 150 or more employees).[6] Firms were chosen from across Korea, with sample firms drawn from the 2008 *Basic Survey of Establishments*. The survey was conducted in the form of interviews and the survey period was July to October, 2010. Details of the number of firms contacted and the number of firms responding are provided in Table 1(b).

In our survey undertaken in China, unfortunately, we were unable to cover the entire country due to budget limitations and we therefore focused on firms in Shanghai, Beijing, Guangzhou, and Shenzhen. Sample firms were drawn from the *Year Book of Chinese Companies* for Shanghai and a list of companies provided by the State Administration for Industry and Commerce for Beijing, Guangzhou, and Shenzhen. Firms were chosen on the basis of random sampling. The survey was implemented in the form of interviews at the firms conducted by interviewers specializing in company surveys. The survey period was August to October, 2010. Details of the number of firms contacted and the number of firms responding are provided in Table 1(c).

As detailed in Introduction, a novelty of our questionnaire survey is that we have devised an objective way to measure integrality of product architecture as a continuous variable ranging from 0 to 100. We used the following question:

"*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?*"

The rest of the variables used in the empirical analysis are reported in Table 2.

[6]It should be noted that because the 2008 *Basic Survey of Establishments* which we used to obtain our sample is the 2008 edition and because of subsequent changes in the number employees, the sample of manufacturing firms contains firms with fewer than 300 employees.

5. Empirical Strategy

This section outlines the empirical strategy to test the theoretical prediction from section 3 using the survey data described in the previous section.

The theoretical prediction can be summarized as follows: "As consumer's valuation of product quality V increases, the firm increases its investment y in reducing its engineers' turnover rate. Decreased turnover rate t by the investment, in turn, increases benefit from the choice of more integral product architecture, and this increases the integrality of architecture x." We test this theoretical prediction using the 2SLS procedure.

In terms of the 2SLS method, our theoretical prediction can be interpreted as follows. First, consumers' valuation of product quality decreases engineers' turnover rate. Second, the reduced turnover rate, in turn, makes the firm choose more integral product architecture. Thus, the first-stage estimation equation can be formulated as follows:

$$t_i = \alpha + \beta V_i + Z_i'\delta + \varepsilon_i,$$

where t_i is the engineers' turnover rate, V_i is the consumers' valuation of product quality, Z_i are the other covariates, and ε_i is the stochastic disturbance of firm i.

In the second stage, we test the prediction that the engineer's turnover rate (which is determined by consumers' valuation of product quality) determines integrality of product architecture by estimating the following equation:

$$x_i = \zeta + \eta \widehat{t_i} + Z_i'\theta + \nu_i,$$

where $\widehat{t_i}$ is the predicted value of the turnover rate derived from the first-stage estimation result.

Next, we explain how to construct key variables in the equations from our data. The questionnaire does not ask about the engineer's turnover rate, t_i, directly. Therefore, we use average tenure years as an inverse proxy for the turnover rate. Because it is the inverted value of the turnover rate, the signs of the coefficients have to be interpreted inversely; that is, *positive* values of β and η are consistent with the theoretical prediction. One may raise the objection, however, that the raw value of tenure years depends heavily on the average age of the firm's employees. For example, the average tenure years of a firm that employs younger engineers is lower than the average tenure years of a firm that employs older engineers, even if both firms have the same turnover rate. To respond to this potential criticism, we use normalized average tenure, which is the job tenure divided by the average age of the firm's employees.

In order to capture integrality of product architecture x_i, as explained in the previous section, we use a continuous measure of integrality ranging from 0 to 100, where a larger value means higher integrality. We use the natural logarithm for this variable.

For the variable of consumers' valuation of product quality V_i, the second key variable, we use information as to how the respondents evaluated the current man-hours spent on the optimization of the product's design parameters, and why they formed such evaluations. In the questionnaire, the respondents were requested to choose the top three reasons from eight options presented. The eight options included three factors for which the current labor-hours are required: (1) quality; (2) function; and (3) downsizing of the product.[7] For example, the choice of "the current man-hours are required for quality" can be interpreted as meaning that the firm is faced with consumers' strong demand for product quality. Against this background, we generate three dummies indicating the demand for quality, function, and downsizing as proxies for the parameter for consumers' valuation of product quality, V.

Other than the above key variables, the survey data provide information on the firm and product specific characteristics that may be correlated with the choice of product architecture and tenure years. For example, larger firms might have a tendency to choose more integral architecture. Also, a firm's management policy could be correlated with integrality of its product architecture. These should be included as other covariates Z_i. For firm characteristics, we include the number of employees, firm age, a dummy variables for a firm being in the machinery industry and the non-machinery industry (the baseline is the software industry), a functional organization dummy that takes the value of one if the firm's organization is a functional system (a traditional structure in which an organization is divided based on functions performed by particular groups of people, such as human resources, manufacturing, and marketing) or zero otherwise, and a professional career ladder dummy that takes the value of one if the firm has a career progression path for engineers (vis-à-vis managers) and zero if it does not. We also introduce a measure of intensiveness of pecuniary

[7]Other options are as follows. The current man-hours are required due to: (1) the pressure for cost reduction; (2) the pressure for quick delivery; (3) the availability of a reusable platform; (4) the lack of organizational capability; and (5) the intensive use of standardized components.

rewards to motivate engineers.[8] Further, to control product-specific characteristics, we include the share of product specific parts, openness of the product interfaces, and a make-to-order dummy that takes the value of one if the product of the firm is make-to-order and zero otherwise.

6. Results and Discussion

The results are shown in Table 3. The upper panel indicates second-stage results, and the lower panel shows first-stage results. Each column shows the results in each country. First, in Japan (Column 1) coefficients of the demand for quality and the demand for function are both positive and significant in the first stage. That is, demand for high quality and the demand for high function of the product increase the average tenure years (reduces engineers' turnover rate). This supports the first part of our theoretical prediction that the demand for quality reduces the turnover rate. Further, Hansen's J statistics do not reject the over-identification condition, and the F-statistics reject a null hypothesis that all coefficients in the first stage are zero. These statistics support the validity of our specifications. Next, in the second stage, the coefficient for the logarithm of normalized tenure years is positively significant. Put differently, the longer normalized tenure years (the lower turnover rate) is associated with a higher level of integrality of product architecture. This supports the second part of our theoretical prediction that a reduction in engineers' turnover rate induces the firm to choose more integral product architecture. Overall, in Japan, empirical results strongly support both parts of our theoretical prediction.

In the case of China (Column 3), the results also support both parts of our theoretical prediction. In the first stage, demand for quality and downsizing are positive and significant at least at the 10% level. It is worth noting that, in contrast to Japan, in China, the demand for downsizing instead of the demand for function is significantly positive. Further, in the second stage, the coefficient for the logarithm of normalized tenure years is positively significant at the 10% level. Hansen's J statistics do not reject the over-identification condition, and the F-

[8] In the questionnaire, we asked the following question. "To motivate engineers, what do you think about the effectiveness of pecuniary compensation such as merit increases or bonuses?" The responses were coded as follows: 1=very effective, 2=effective, 3=neither effective nor ineffective, 4=ineffective, and 5= very ineffective. The averages were 2.0 for Japan, 1.8 for Korea, and 1.3 for China, respectively. This suggests that pecuniary compensation is most effective in China.

statistics reject a null hypothesis that all the coefficients in the first stage are zero. Thus, both parts of our theoretical prediction are also supported in China.

On the other hand, in Korea, we cannot obtain a result that supports our theoretical prediction. In the first stage, the coefficients for the demand for function and downsizing are significant but negative. In the second stage, the coefficient for the logarithm of normalized tenure years is not significant.

A possible reason for the absence of support in Korea for our theoretical prediction is that Korean firms tend to produce multiple products with variable integrality of their architecture. In our questionnaire survey, the information about integrality and consumers' valuation of product quality are product-specific, whereas engineers' turnover rate is firm-level information. If a firm develops and manufactures products with a wide range of integrality of product architecture, the firm's engineers' average turnover rate might not be optimal for its representative product. In fact, Korean firms are in the transition process of their focus from low-quality to high-quality products, and hence many firms produce multiple products with variable quality. This suggests a possibility that many Korean firms develop and manufacture multiple products with variable integrality of product architecture. On the other hand, Japanese and Chinese firms tend to produce products with a narrower range of product qualities, suggesting a better match between product and firm-specific information (Tsuru & Morishima, 2011).

In sum, both parts of our theoretical prediction find empirical support in Japan and China, but not in Korea. Positively significant β in the first stage can be interpreted as being that exogenous consumers' valuation of product quality has a positive effect on the average tenure years of the engineers. It is consistent with the first part of our theoretical prediction that in response to consumers' valuation for quality, the firm reduces the turnover rate to increase the global optimality of quality. Furthermore, positively significant η in the second stage can be interpreted as being that the predicted value of the average tenure years affected by consumers' valuation for quality has a positive effect on the integrality of product architecture. This is consistent with the second part of our theoretical prediction that a lower turnover rate induces more integral product architecture.

7. Conclusions

A firm's choice of product architecture is a key determinant of product quality and a critical element of firms' decisions about their strategies for product innovation. We have explored interrelationships among the choice of product architecture, engineers' ability to coordinate their activities on component design, and consumers' valuation of product quality. In our theoretical model, as a firm chooses higher integrality for the architecture of a product, its global quality increases at the expense of increasing interactions between engineers' design activities.

Our model, which has contributed to the organizational economics literature of intra-firm coordination by endogenizing the degree of interdependence between individuals workers' actions, yielded the following testable prediction: "As consumers' valuation of product quality increases, the firm invests more to reduce engineers' turnover rate. A lower turnover rate, in turn, increases the integrality of the product architecture." We investigated this prediction empirically by analysing data we collected through administration of questionnaire surveys to manufacturing and software companies in Japan, Korea, and China, and found empirical support for our both parts of our theoretical prediction in Japan and China but not in Korea.

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Appendix

[Proofs of Propositions 1 and 2]

Let (x, y) be given. First suppose that both engineers remained with the firm at Stage 2. Having observed both θ_i and θ_j, in the subsequent equilibrium each engineer i chooses a_i to maximize the local quality $L_i(a_i, a_j) = -(a_i + xa_j - \theta_i)^2$, correctly anticipating a_j. This implies that each engineer i's equilibrium action a_i^* is given by $a_i^* = \frac{\theta_i - x\theta_j}{1-x^2}$(i, j = 1, 2, i ≠ j), where $(a_1, a_2) = (a_1^*, a_2^*)$ solves the simultaneous equations (A1) and (A2):

(A1) $a_1 + xa_2 - \theta_1 = 0$

(A2) $a_2 + xa_1 - \theta_2 = 0$

Hence, in every no-turnover subgame, equilibrium local qualities are $L_1(a_1^*, a_2^*) = L_2(a_2^*, a_1^*) = 0$, and so equilibrium quality, denoted $q_{no\text{-}turnover}$, is given by:

(A3) $q_{no\text{-}turnover} = G(x) + L_1(a_1^*, a_2^*) + L_2(a_2^*, a_1^*) = R + kx.$

Next suppose that at least one engineer turned over at Stage 2. Let $a_i(\theta_i)$ denote each engineer i's equilibrium action as a function of θ_i. Having observed θ_i, in the subsequent equilibrium each engineer i chooses a_i to maximize the expected value of $-(a_i + xa_j(\theta_j) - \theta_i)^2$, correctly anticipating $a_j(\theta_j)$. This implies that $a_i(\theta_i) = \theta_i - xE[a_j(\theta_j)]$ (where $E[a_j(\theta_j)]$ denotes the expected value of $a_j(\theta_j)$) holds for i, j = 1, 2. We then have (A4) and (A5):

(A4) $E[a_1(\theta_1)] + xE[a_2(\theta_2)] = E(\theta)$

(A5) $xE[a_1(\theta_1)] + E[a_2(\theta_2)] = E(\theta)$

Solving (A4) and (A5) we find that $E[a_i(\theta_i)] = \frac{E(\theta)}{1+x}$holds, and hence $a_i(\theta_i) = \theta_i - \frac{x}{1+x}E(\theta)$for i = 1, 2. Let $q_{turnover}$ denote the expected value of equilibrium quality in the turnover subgame. We find that $q_{turnover}$ is given by:

(A6) $q_{turnover} = G(x) + E[L_1(a_1(\theta_1), a_2(\theta_2))] + E[L_2(a_2(\theta_2), a_1(\theta_1))] = R + kx - 2x^2Var(\theta).$

Let q*(x, y) denote the expected value of the equilibrium product quality as a function of (x, y). Given (A3) and (A6), we find that q*(x, y) is given by (A7), where $B \equiv Var(\theta)$.

(A7) $q^*(x, y) = tq_{turnover} + (1-t)q_{no\text{-}turnover} = R + kx - 2tBx^2.$

At stage 1, the firm chooses (x, y) to maximize its expected overall profit in the subsequent equilibrium, which is denoted π(x, y) and given by:

(A8) $\pi(x, y) = Vq^*(x, y) - c(y) = V[R + kx - 2tBx^2] - \frac{1}{2}y^2.$

Consider the following maximization problem:

(A9) $\text{Max}_{\{x, y\}}\pi(x, y)$ subject to $x \in [0, \eta]$ and $y \in [0, T]$

We have that $\frac{\partial}{\partial y}\pi(x, y) = 2VBx^2 - y$. Then, given $\eta < \sqrt{\frac{T}{2VB}}$ (Assumption 1), for any given x $\in [0, \eta]$ the unique optimal value of y is given by (A10):

(A10) $y = 2VBx^2 \equiv f(x)$

The maximization problem (A9) is then equivalent to (A11):

(A11) $\text{Max}_{\{x\}}\pi(x, f(x))$ subject to $x \in [0, \eta]$,

where $\pi(x, f(x)) = V[R + kx - 2TBx^2 + 2VB^2x^4] \equiv g(x)$.

Weierstrass Theorem ensures the existence of a solution to (A11), denoted x*. We have (A12) and (A13):

(A12) $g'(x) = V[k - 4Bx(T - 2VBx^2)]$

(A13) $g''(x) = V(-4TB + 24VB^2x^2)$

First suppose k = 0. Then $g'(0) = 0$ and $g'(x) < 0$ for all $x \in (0, \eta]$. Hence (A11) has a unique solution $x^* = 0$. We now establish Claim 1, which implies Proposition 1.

Claim 1: Suppose k > 0. Then there exists a unique value K > 0 such that (A11) has a unique solution $x^* = \eta$ if k > K and a unique solution $x^* \in (0, \eta)$ if k < K. Also, if k = K, (A11) has a unique solution $x^* = \eta$ if $\eta \leq \sqrt{\frac{T}{6VB}}$, and two solutions (one is $x^* = \eta$ and the other satisfies $x^* \in (0, \eta)$) otherwise.

[Proof] We have that $x = \min\{\eta, \sqrt{\frac{T}{6VB}}\} \equiv \tilde{x}$ maximizes the value of $4Bx(T - 2VBx^2)$ subject to $x \in [0, \eta]$. Define $\tilde{k}$ and $\hat{k}$, respectively, by $\tilde{k} = 4B\tilde{x}(T - 2VB\tilde{x}^2)$ and $\hat{k} = 4B\hat{x}(T - 2VB\hat{x}^2)$. We have that $\tilde{k} \geq \hat{k} > 0$, where $\tilde{k} = \hat{k} \leftrightarrow \eta \leq \sqrt{\frac{T}{6VB}}$.

(i) Suppose $k \geq \tilde{k}$. We then have that $g'(x) \geq 0$ for all $x \in [0, \eta]$, and $g'(x) > 0$ in the neighbourhood of $x = \eta$ with $x < \eta$. This implies that (A11) has a unique solution $x^* = \eta$.

(ii) Suppose $k < \tilde{k}$. Then $g'(x) < 0$ holds for some x in $[0, \eta]$. We have that $g'(0) > 0$, $g''(0) < 0$, and $g''(x)$ is strictly increasing in x for all $x \in (0, \eta]$. This implies that there exists a unique value $x' \in (0, \eta)$ such that g(x) achieves a local maximum in $(0, \eta)$ when $x = x'$. Then there are only two candidates for the global maximum, $x^* = x'$ and $x^* = \eta$.

(ii – 1) Suppose $\tilde{k} = \hat{k}$. Then $g'(\eta) < 0$ holds for all $k < \tilde{k}$. This implies that $g(x') > g(\eta)$ for all $k < \tilde{k}$. Hence (A11) has a unique solution $x^* = x'$ in this case.

(ii – 2) Suppose $\tilde{k} > \hat{k}$. Then g′(η)> 0 holds if k $\in (\hat{k}, \tilde{k})$, whereas g′(η) ≤ 0 if k ≤ $\hat{k}$. We have that $\frac{d}{dk}$ g′(x) > 0 for all x ∈ [0, η]. This implies that there exists a unique value $\bar{k} \in (\hat{k}, \tilde{k})$ such that g(x′) < g(η) if $k \in (\bar{k}, \tilde{k})$, g(x′) = g(η) if k = $\bar{k}$, and g(x′) > g(η) if k <$\bar{k}$.

Then, defining K by K = $\tilde{k}(= \hat{k})$ if $\eta \leq \sqrt{\frac{T}{6VB}}$ and K = $\bar{k}$ otherwise completes the proof. *Q.E.D.*

Finally, to prove Proposition 2, suppose 0 < k < K. Then g′(x) > 0 for all x ∈ [0, x*] and g′(x*) = 0 where x* ∈ (0, η). We then have that $\frac{d}{dV}$ g′(x) > 0 and $\frac{d}{dk}$ g′(x) > 0 for all x ∈ [0, x*]. This proves Proposition 2. *Q.E.D.*

Table 1. Details of Questionnaire Surveys

(a) Japan

		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.

(b) Korea

		Population	No. of responses	Response rate
Total		738	140	19.0%
No. of employees	Fewer than 300	69	38	55.1%
	300-499	354	34	9.6%
	500-999	194	40	20.6%
	1,000 or more	121	28	23.1%
Industry	Manufacturing	656	121	18.4%
	Software Industry	82	19	23.2%

Notes: 1. Sample firms were drawn from the 2008 *Basic Survey of Establishments.*

2. Firms with more than 300 employees (manufacturing sector) and 150 employees(software sector) only.

(c) China

Region	Industry	Population	Firms contacted	No. of responses	Response rate
Shanghai	Manufacturing	5,558	487	35	7.2%
	Software	188	57	5	8.8%
Beijing	Manufacturing	9,792	403	30	7.4%
	Software	206	132	10	7.6%
Guangzhou	Manufacturing	27,481	528	35	6.6%
	Software	117	52	5	9.6%
Shenzhen	Manufacturing	17,215	341	30	8.8%
	Software	9	0	0	-

Notes: 1. Sample firms were drawn from the *Year Book of Chinese Companies* (Shanghai) and a list of companies provided by the State Administration for Industry and Commerce(Beijing, Guangzhou, Shenzhen).

2. Firms with more than 300 employees (manufacturing sector) and 50 employees (software sector) only.

Table 2. Summary Statistics

	Total			Japan			Korea			China		
	Observations	Mean	SD	Observations	Mean	SD	Observations	Mean	SD	Observations	Mean	SD
Engineers' average age	384	34.03	5.99	94	37.67	3.81	140	35.34	7.46	150	30.52	2.98
Engineers' average tenure years	383	7.96	4.74	93	12.82	4.48	140	7.69	4.60	150	5.20	1.76
Engineers' normalized tenure years	379	0.23	0.11	93	0.34	0.10	136	0.21	0.10	150	0.17	0.05
Integrality of the product	357	44.45	23.22	75	41.53	23.85	132	47.59	27.77	150	43.15	17.67
Demand for quality	394	0.79	0.41	104	0.54	0.50	140	0.87	0.34	150	0.89	0.32
Demand for function	394	0.53	0.50	104	0.44	0.50	140	0.67	0.47	150	0.46	0.50
Demand for downsizing	394	0.11	0.32	104	0.09	0.28	140	0.07	0.26	150	0.17	0.38
ln(Share of product specific parts)	349	3.68	0.73	68	3.52	0.94	131	3.75	0.84	150	3.70	0.47
ln(Openness of product interfaces)	362	3.80	0.64	77	3.82	0.69	135	3.79	0.77	150	3.81	0.48
No. of workers	394	749.07	1743.85	104	864.22	2657.62	140	851.20	1523.22	150	573.90	961.25
Firm age	394	29.05	20.83	104	50.87	15.27	140	31.01	17.48	150	12.09	8.53
Machinery dummy	394	0.38	0.48	104	0.42	0.50	140	0.52	0.50	150	0.21	0.41
Non machinery dummy	394	0.49	0.50	104	0.43	0.50	140	0.34	0.48	150	0.66	0.48
Functional organization dummy	394	0.62	0.49	104	0.46	0.50	140	0.66	0.47	150	0.69	0.47
Professional leader dummy	394	0.39	0.49	104	0.21	0.41	140	0.42	0.50	150	0.48	0.50
Pecuniary rewards	392	1.68	0.69	102	1.96	0.61	140	1.83	0.71	150	1.35	0.57
Make-to order dummy	385	0.65	0.48	95	0.73	0.45	140	0.66	0.48	150	0.61	0.49

Table 3. Regression Results, Two Stage Least Squares

Country	(1) Japan	(2) Korea	(3) China
Second-stage results Dependent: ln(product architecture)			
ln(normalized tenure years)	2.431 **	-0.408	0.676 *
	(0.797)	(1.130)	(0.395)
Importance of coordination between components	0.00270	-0.360 *	-0.126 **
	(0.141)	(0.184)	(0.0568)
ln(Share of product specific parts)	-0.0579	0.209 **	0.0111
	(0.123)	(0.103)	(0.0988)
ln(Openness of product interfaces)	0.316	0.241	0.228 **
	(0.201)	(0.199)	(0.0970)
ln(No. of employees)	-0.132	-0.00892	0.0724
	(0.121)	(0.138)	(0.0526)
ln(Age)	-0.623	-0.0110	0.0738
	(0.496)	(0.303)	(0.0567)
Dummy for machinery industry	0.237	0.179	-0.358 *
	(0.275)	(0.412)	(0.192)
Dummy for non-machinery industry	0.500	0.0394	-0.315 *
	(0.338)	(0.580)	(0.161)
Dummy for functional organization	0.213	-0.133	0.0591
	(0.185)	(0.188)	(0.0694)
Dummy for professional career ladder	-0.0166	0.288 **	0.199 **
	(0.207)	(0.145)	(0.0673)
Intensiveness of pecuniary rewards	-0.213	0.0287	0.234 **
	(0.141)	(0.154)	(0.0669)
Dummy for make-to-order	-0.490 *	-0.343 *	0.158 **
	(0.291)	(0.194)	(0.0698)
Constant	14.75 **	1.531	3.223 **
	(3.872)	(6.982)	(0.870)
Hansen's J statistics (p-value)	0.1782	0.1991	0.1669
Observations	66	123	150
First-stage results Dependent: ln(normalized tenure years)			
Demand for quality	0.133 *	-0.0915	0.193 **
	(0.0732)	(0.0900)	(0.0706)
Demand for function	0.199 **	-0.138 *	0.0583
	(0.0750)	(0.0830)	(0.0505)
Demand for downsizing	-0.0495	-0.297 **	0.114 *
	(0.113)	(0.147)	(0.0640)
Other covariates	yes	yes	yes
F-stat (p-value)	0.000	0.000	0.000
Adjusted R-squared	0.291	0.267	0.105
Observations	67	126	150

Note: Robust standard errors in parentheses.
Figures in parentheses are standard errors. **and * indicate statistical significance at the 5% and 10% level, respectively.