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

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Abstract

Coordination within organizations has been recognized as an issue of central importance in the organizational economics literature, where the degree of interdependence between individuals' actions is taken as given. In reality, however, the degree of interdependence is affected by the choice of an organization's strategy, and hence there are inter-relationships among the interdependence of individuals' actions within organizations, their ability to coordinate their actions, and the choice of the organization's strategy.

We explore these inter-relationships by focusing on coordination between engineers. In our theoretical model, we consider a firm that designs and sells a product which consists of two components, 1 and 2. Engineer i (= 1, 2), who is in charge of the design of component i, attempts to maximize component i's quality (local quality). The degree to which designs of different components interact with each other is a key determinant of success in product development. In this context, previous research on product design has found that *product architecture* is a useful concept. In our model, a firm can increase the product's global quality by increasing the integrality of the product's architecture. Higher integrality, however, also increases the degree of interaction between the two components' designs, making coordination between engineers more important. We hypothesize that the longer the engineers work together the better they can coordinate their actions.

Our model yields 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 investigate this prediction empirically by analysing data we collected through administration of questionnaire surveys to manufacturing and software companies in Japan, Korea, and China. A novelty of our questionnaire survey is that it measures the integrality of product architecture with a continuous variable ranging from 0 to 100, whereas previous studies on product architecture are based on a dichotomy of modular or integral architecture. We test our theoretical prediction by the two-stage least squares procedure, and find empirical support for our theoretical prediction in Japan and China but not in Korea. We discuss possible reasons for the lack of empirical support in Korea.

1. Introduction

Organizations consist of multiple individuals (or divisions), in which actions taken by individuals (or division managers) determine organizations' overall performance levels. These actions require coordination when they are interdependent. 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)). The degree of interdependence between individuals' actions is taken as given in the existing analyses of intra-firm coordination. In reality, however, the degree of interdependence is affected in significant ways by the choice of the organization's strategy. Hence, there are inter-relationships among interdependence of individuals' actions within organizations, their ability to coordinate their actions, and choice of organizational strategy.

The objective of this paper is to explore these inter-relationships, both theoretically and empirically, by focusing on coordination between engineers within organizations. Most products consist of a number of different components. In the development of such products, it is rare for one single engineer to be in charge of an entire product. In most cases, a number of engineers (or groups of engineers) are involved, and each engineer (or group of engineers) attempts to optimize the function of the assigned component. Hence the degree to which designs of different components interact with each other is a key determinant of success in product development.

Previous research on product design has found that a distinction between *modular* architecture and *integral* architecture is useful in this context (see Ulrich (1995) for a seminal contribution to the literature on product architecture). Under modular architecture, the design of one component is independent of the design of other components, whereas under integral architecture, the design of one component affects and interacts with the design of other components. The advantage of modular architecture is that it requires no coordination between engineers in charge of different components. That is, each engineer can focus on optimizing the function of the assigned component without worrying about its interactions with other components. In contrast, component interactions generated by integral architecture may impose a challenge for each engineer to optimize the function of the assigned component. The advantage of integral architecture is that it can increase the product's *global quality,* which arises from the properties of most components of the product (in contrast, *local quality* refers to the quality of each component).

In what follows, we explain the trade-off regarding integral vs. modular architecture though use of a stylized example (our explanation here is based on Ulrich (1995), who used motorcycles and automobiles as concrete examples).Let us consider a product that performs three functions, denoted by A, B, and C. Product quality consists of global quality and local quality. We consider the size of the product as an example of global quality (the smaller the better). Functions are implemented by physical components, and recall that local quality is the quality of each component. Mapping between functions and components may be one-to-one, many-to-one, or one-to-many.[1] Regarding specification of interfaces, a key concept is interface coupling; two components are coupled if a change made to one component requires a change to the other component, whereas they are de-coupled otherwise.

Under modular architecture, each function is mapped into one component (one-to-one mapping), and the design of each component does not affect the design of other components (de-coupled interfaces). 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. 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.

As illustrated by the example, the choice of integral architecture increases the global quality of the product at the expense of an increase in component interactions. Hence the optimal choice of product architecture is related in important ways to engineers' abilities to coordinate with each other in component designs, and the degree to which consumers value product quality. Nevertheless, to the best of our knowledge, interrelationships among these three elements have not yet been explored in the literature.

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[1] The mapping is one-to-one if function A is implemented by component a, function B is implemented by component b, and function C is implemented by component c. It is many-to-one if, for example, function A is implemented by component a, function B is jointly implemented by components a and b, and function C is implemented by component b.

We analyze, both theoretically and empirically, the choice of product architecture in its relationship to engineers' actions to coordinate with each other and the degree to which consumers value product quality. In our theoretical model, we consider a firm that designs and sells a product consisting of two components, 1 and 2. The quality of the product is determined by the combination of its global quality and each component's local quality. 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 to maximize the local quality associated with component i.

In reality, the choice of product architecture is not based on a dichotomy of "completely modular or completely integral" but rather is based on a continuum between these two extremes.[2] Our model incorporates this reality by assuming that the firm chooses the nature of the product's architecture, denoted $x \in [0, \eta]$, where architecture is completely modular when $x = 0$ and where the integrality of architecture increases as x increases. When $x = 0$, each engineer i's action has no effect on the design of component j ($\neq$ i). That is, when product architecture is completely modular, the design of each component is completely independent of the design of the other component. As x increases, the effect of each engineer i's action on the design of component j increases. That is, as the integrality of product architecture increases, interaction in the design of the two components increases. At the same time, global quality of the product increases as the integrality of product architecture increases.

We hypothesize that the longer the engineers work together the better they can coordinate their actions. We incorporate this hypothesis in our model in a reduced form. We assume that both engineers work for the firm for a sufficiently long period of time with probability $1 - t$ ($t \in (0, 1)$) and interpret t as the engineers' turnover rate. We then assume that, if there is no turnover, the engineers' coordination is perfect at any level of integrality x, whereas their coordination is imperfect if there is turnover. We also assume that the firm can reduce the turnover rate by investing more in its efforts to retain engineers.

Our theoretical model yields the following testable theoretical prediction: "As consumers' valuation of product quality increases, engineers' turnover rate decreases. A lower turnover rate, in turn, increases the integrality of product architecture." The logic behind this prediction can be explained as follows. The quality of the firm's product is higher

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[2] Ulrich (1995), for example, pointed out, "In most cases the choice will not be between a completely modular or completely integral architecture, but rather will be focused on which functional elements should be treated in a modular way and which should be treated in an integral way."(p.437)

under no turnover because the engineers can perfectly coordinate their actions to maximize local quality under no turnover, whereas their coordination is imperfect if turnover occurs. Hence, as consumers' valuation of product quality increases, the firm increases its investment in reduction of the turnover rate to increase expected product quality. The lower turnover, in turn, induces the firm to increase the integrality of 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 increase its investment in reducing the turnover rate.

We investigate this prediction empirically by analysing data we collected through administration of questionnaire surveys to manufacturing and software companies in Japan, Korea, and China. A novelty of our questionnaire survey is that it measures integrality of product architecture with a continuous variable ranging from 0 to 100, whereas previous studies on product architecture are based on the dichotomy of modular or integral architecture which, as noted, is not a true representation of reality. Our survey also contains information that can be used as proxies for engineers' turnover rate and consumers' valuation of product quality.

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)). This does not, however, rule out the possibility that some Japanese firms adopt modular architecture to produce standardized products, or that some Chinese firms adopt integral architecture. The small sample feature of case studies is not suitable to capture the entire picture of the choice of architecture in Japan and China. 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.

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' turnover rate. We test this in the first-stage estimation, where a negative coefficient for consumers' valuation (which is an exogenous explanatory variable) supports our prediction. Next, as the turnover 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 negative coefficient for the estimated turnover rate supports our prediction.[3]

We find empirical support for our prediction for the Japanese and Chinese cases, but not for the Korean case. We suspect that a possible reason for the lack of support in the Korean data relates to the nature of our questionnaire survey. In our questionnaire survey, information about integrality and consumers' valuation of product quality are product-specific information and we asked respondents for a representative product of the firm, 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 different integrality of their architectures. 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-specific information and firm-level information

The rest of the paper proceeds as follows. In Section 2, we formulate the model for determining engineers' turnover rate and the degree of integrality or modularity of product architecture. 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

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[3] 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.

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 quality level 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 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 $c(y) = \frac{1}{2}y^2$ to obtain closed-form solutions in the analysis.

On the demand side, there are 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: $\eta < \sqrt{\frac{T}{2VB}}$.

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 $q_{\text{no-turnover}}=G(x) = R + kx$.

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 $q_{\text{turnover}} = R + kx - 2x^2\text{Var}(\theta)$, which is below $q_{\text{no-turnover}}$ because each engineer i cannot observe θ_j and hence cannot correctly anticipate a_j in turnover subgames. The difference between $q_{\text{no-turnover}}$ and q_{turnover}, $2x^2\text{Var}(\theta)$ increases as the integrality of product architecture x increases and as the variance of the local condition $\text{Var}(\theta)$ 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) $$q^*(x, y) = tq_{\text{turnover}} + (1 - t)q_{\text{no-turnover}} = R + kx - 2tx^2\text{Var}(\theta).$$

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

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

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:[4]

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

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

(iii) If $k > K$, $x^* = \eta$ and $y^* = 2V\text{Var}(\theta)\eta^2$ hold.

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

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 ($x = \eta$), 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.

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

In order to examine the prediction described in the previous section, we administered a firm-level questionnaire survey. The survey questionnaire was identical for all three countries, and the actual survey was conducted after a pretest.

The details of the survey are as follows. In the case of Japan, the target firms 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).[5] 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

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[5] 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.

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).

A novelty of this questionnaire survey is that it provides information on integrality of product architecture as a continuous variable ranging from 0 to 100. The actual question is 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?*"

The critical part of this question is "optimizing the design parameters of the 'key component' in order to achieve the desired function." Design typically involves two processes. The first step is functional design, in which the firm determines the *desired function* of the product. The second step is structural design, which specifies the relationship among components (the *design parameters*), corresponding to the *desired function*. The design parameters, by themselves, mean technological relationships among components. Behind the technological relationships, there are coordinating activities by designers. In other words, observed technological relationships are an outcome of designers' actions for coordination (Baldwin & Clark, 2000, pp.33-39).

To achieve the highest development performance possible, the firm should "*optimize the design parameters*," given the desired function. As explained above, because the design parameters express the technological relationships among components, it is not possible to observe directly whether the firm has optimized them. For this reason, we need some observable measure. A natural candidate for the observable measure is engineers' man-hours spent on the optimization.

In this sense, the answer to the above question was to determine whether the percentage was relatively low, in which case the relationship among the components is relatively simple, indicating a modular architecture, or whether it was relatively high, suggesting that the relationship among the components is relatively complex, indicating integral product architecture. The rest of the variables used in the empirical analysis are reported in Table 2.

5. Empirical Strategy

In section 3, we obtained a testabletheoretical prediction. This section outlines the empirical strategy to test the prediction 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.

Our theoretical prediction can be interpreted in terms of the 2SLS method. 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 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 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.[6] 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

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[6] 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.[7] 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-

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[7] 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

Product architecture is a key determinant of product quality and the degree of interaction between different components. Choice of product architecture is therefore 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' 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.

References

Baldwin C.Y. and Clark, K.B. (2000) *Design Rules*, Cambridge, Massachusetts: MIT Press.

Clark, K.B. and Fujimoto, T. (1991) *Product Development Performance: Strategy Organization and Management in the World Auto Industry*, Boston: Harvard Business School Press.

Fujimoto, T. (2001) “Architecture no sangyoron [An architecture-based analysis of industry],” in T. Fujimoto, A. Takeishi, and Y. Aoshima, eds., *Business Architecture*, Tokyo: Yuhikaku, 3-26 (in Japanese).

Fujimoto, T. and Shintaku, J. (2005) *Chugoku Seizogyo no Architecture Bunseki [An Analysis of Product Architecture in Chinese Manufacturing Industry]*, Tokyo: Toyo KeizaiShinposha (in Japanese).

Milgrom, P. and Roberts, J. (1992) *Economics, Organization and Management*, Englewood Cliffs, New Jersey: Prentice-Hall.

Roberts, J. (2004) *The Modern Firm: Organizational Design for Performance and Growth*, Oxford: Oxford University Press.

Tsuru, T. and Morishima, M. (2011) “Product Architecture, Organizational Design, and HRM Practices: Comparing Japanese, Korean, and Chinese Firms,” Hitotsubashi University, Fukino Project Discussion Paper Series No. 27.

Ulrich, K. (1995) “The Role of Product Architecture in the Manufacturing Firm,” *Research Policy*, 24, 419-440.

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 $q_{\text{no-turnover}}$, is given by:

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

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

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 $B \equiv \text{Var}(\theta)$.

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

At stage 1, the firm chooses (x, y) to maximize its expected overall profit in the subsequent equilibrium, which is denoted $\pi(x, y)$ 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) $\mathrm{Max}_{\{x\}}\pi(x, f(x))$ 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* = η if k > K and a unique solution $x^* \in (0, \eta)$ if k < K. Also, if k = K, (A11) has a unique solution x* = η if $\eta \le \sqrt{\frac{T}{6VB}}$, and two solutions (one is x* = η 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 $\tilde{k} \ge \hat{k} > 0$, where $\tilde{k} = \hat{k} \leftrightarrow \eta \le \sqrt{\frac{T}{6VB}}$.

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

(ii) Suppose $k < \tilde{k}$. Then $g'(x) < 0$ holds for some x in [0, η]. 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, η) when x = x′. Then there are only two candidates for the global maximum, x* = x′ and x* = η.

(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.