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5-2009

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ABSTRACT

Researchers have proposed that modular products lead to modular organizations. However empirical evidence today has been conflicting, and, moreover, the details of how modular products drive modular organizations have not been explored. In this study, by analyzing the structure of OSS development team, we extend prior research in three important ways: First we show that the number of modules a product has will increase the modularity in the organization. Second, the sheer size of contributors will contribute to organizational modularity. Third, we show that organizational modularity is a dynamic concept and tends to vary during different stages of the product development life cycle. Our findings have important theoretical and practical implications.

Keywords

Modular products, modular organizations, open source software development.

INTRODUCTION

It has been recognized that organizational design appears to be shifting away from the hierarchical, bureaucratic structure towards more flexible, interconnected, and coordinated self-organizing structure (Daft and Lewin, 1993), and increasingly the resulting organizations take on the forms of modular organization, virtual corporation, spinout corporation, cluster organization, and network organization, etc. These new forms of organizations tend to have flatter hierarchies, decentralized decision making, greater tolerance for ambiguity, permeable internal and external boundaries. At the same time, they typically exhibit properties of empowerment of employees, capacity for renewal, self-organizing units, and self-integrating coordination. Many believe that globalization, demographic shifts, advances in information technology, demassification of society, and hypercompetition are some of the major drivers underneath this shift (Lewin and Volberda, 1999).

One of the issues that have been raised by researchers over the last decade is how product design is related to organizational design, and specifically do modular products lead to modular organizations? Some researchers argue that there is indeed a one-to-one mapping between product and organizational modularity. Breaking up complex products into multiple modules, various portions of the products can be developed in parallel and later integrate into a continuous product, and thus eliminate what would otherwise be an unmanageable spaghetti tangle of systemic interconnection (Langlois, 2002). The information structure emerges from product modularity provides a means to embed coordination of loosely coupled component development process, further causing modular organizational structure (Sanchez and Mahoney, 1996). At industry level, heterogeneity in resource input and output drives modular organizational design through forms of contract, alternative work arrangements, and alliance (Hoetker, 2006; Schilling, 2000; Schilling and Steensma, 2001).

However, empirical evidence for the argument is scarce and inconsistent (Hoetker, 2006), and counter arguments exist (Brusoni and Prencipe, 2001). For example, the industry level results obtained by Shilling and Steensma (2001) are generally regarded as an approximation (Fixson, 2007). In this research, we try to extend prior research and reveal the details of how modular design of a product can possibly lead to modular organization by analyzing the organizational structure of software development team. We make the following contributions: First, our research setting allows us to show a much cleaner relationship than previous studies have demonstrated between modular products and modular organizations. Second, the results show that the decision for adopting or evolving into modular organization depends critically on and the complexity of the products: the more modules products have, the more likely modular organizational forms will be adopted. Third, we show and empirically confirm that the sheer size of the contributors will increase the chance to adopt modular organizational forms. Forth, we reveal that modularity in organizational forms is a dynamic concept, and it varies at different stages of the product life cycle: organizations tend to be less modular at the initial stages of product development life cycle because of the need for idea generation and cross-fertilization. However, as products become more mature and stabilized when routine tasks take over, organizations tend to be more modular.

LITERATURE REVIEW

Modularity is a general systems concept (Ulrich, 1995), and it is a continuum describing the degree to which a system's components can be separated and recombined (Schilling, 2000). The concept of modularity is originally applied to product design (Fixson, 2007). For example, as early as 1914, automobile industry started to standardize the subassemblies for various parts (Swan, 1914). Langlois (2002) argue that modular design arises from complex systems, which are made up of large number of parts that interact in a nonsimple way. One way to manage the complexity is to reduce the number of distinct elements in the system by grouping elements into a smaller number of subsystems, so that the interdependency between each group can be substantially reduced. By developing the ability to produce a wide variety of products through assembling standardized modules, manufacturers can expect to significantly reduce uncertainty and complexity, cut product development time, and lower overall costs (Sanchez, 2000). The benefits of modular design include concurrent development, robust to interruption of the production process, reduced communication cost, and increased quality, etc (Gershenson, Prasad and Zhang, 2003).

Software development is one of the areas that have witness the most mature application of modular design of products (Fixson, 2007). A software module captures a set of design decisions which are hidden from other modules and the interaction among the modules should primarily be through module interfaces, thus modular design promotes encapsulation or information hiding by separating a module's interface from its implementation (Parnas, 1972). Two important index of software modularity is cohesion and coupling (Mancoridis, Mitchell, Rorres, Chen and Gansner, 1998), where cohesion is measured as the ratio of the number of internal function-call dependencies that actually exists to the maximum possible internal dependencies, and coupling is measured as the ratio of the number of actual external function-call dependencies between the two modules to the maximum possible number of such external dependencies.

Over time, the concept of modularity also finds its application in organizational science. In organizational setting, the issue is to decompose the organization of a production process by partitioning tasks among distinct development units (von Hippel, 1990). Later studies extend the concept to inter-organizational collaboration (Sanchez and Mahoney, 1996; Shilling and Steensma, 2001). Researchers have identified increasing modularity in organizational design. For example, many large, integrated, hierarchical organizations are disaggregated into loosely coupled production arrangement, such as contract manufacturing, alternative work arrangement, and strategic alliance (Sanchez and Mahoney, 1996; Shilling, 2000; Shilling and Steensma, 2001).

Sanchez and Mahoney (1996) are among the first to explore how product modularity is related to organizational change from the perspective of product creation process, and they argue that there is a one-to-one mapping between product and organizational modularity. Though there are case studies that focus on some specific examples, large sample empirical research is scarce. Perhaps two most important empirical studies so far are conducted by Shilling and Steensma (2001) and Hoetker (2006). Shilling and Steensma (2001) measure modularity of an industry in three dimensions: contract manufacturing, alternative work arrangement, and alliance formation. The heterogeneity of the input and output of the product is approximated as the count of the commodities. However, their analysis is conducted at industry level, and the exact connection between product and organizational modularity is still not clear.

In an effort to disentangle many of the confounding factors, Hoetker (2006) revisited the problem under the setting of notebook manufacturing industry. The main argument of the study is that, when choosing component suppliers, firms producing modular products will less likely to choose internal suppliers than firms producing systematic products. Yet he found that both modular products and systematic products prefer internal suppliers than external suppliers. It is very likely that when choosing component suppliers there are more important factors that need to be considered than product design, such as economic and political influences. In other word, his finding does not support the hypothesis that modular product leads to modular organization. However, there are some limitations to his study as well: First, the distinction between modular and systematic product is not well supported. Second, there are important confounding factors that are not considered when deciding component suppliers. No matter the product is modular or systematic, internal business partners can reduce transaction cost and also internalize the profit, thus under both product designs, the manufacturers would prefer internal suppliers. In other word, we believe the research context can not answer the question of whether modular product leads to modular design.

In addition, some researchers doubt there exists a one-to-one mapping between product and organizational modularity. For example, through analysis of the aircraft engine and chemical engineering industry, both of which are well-known for their modular design of their product, Brusoni and Prencipe (2001) argue that there is no one-to-one mapping between product and organizational modularity. They argue that, despite the many benefits brought by modular organizations, conceptual design of heavily engineered products demands flexible, highly interactive organizational set-ups, wherein the related and numerous engineering disciplines can interact and cross-fertilize. In addition, coordinating increasingly specialized bodies of knowledge

and increasingly distributed learning processes further requires the presence of knowledge-integrating firms even in the presence of modular products (Brusoni, 2005).

Despite these inconsistent evidences and counter arguments, we believe modular products do lead to modular organizations. Next, we extend the argument by Sanchez and Mahoney (1996) and argue why modular products could possibly lead to modular organizations, and more importantly we extend the prior arguments in three important directions by analyzing how the number of modules, the size of contributors, and the product life cycle affect the modularity of organizations.

THEORY AND HYPOTHESES

In modular product design, each module represents a different product function or task, which further requires different input of resources and technologies. Each module, at the extreme, could become the sole business of a specialist firm, which would have complete design authority over the specific modules on which it focuses (Brusoni, 2005). One of the criteria for achieving good modular design for products is information hiding, the result of which is loose coupling between modules and high cohesion within modules. Typically organizational members or subsets of an organization also possesses various expertise due to heterogeneous endowment (Barney, 1991), thus the production process is basically a matching process between the task requirements and member expertise. This view is supported in the growing literature on division of labor and knowledge. For example, by focusing on a specific module, each member or team would be able to specialize its learning and innovative efforts (Arora, Gambardella and Rullani, 1997). When the number of the modules increases, organizational subsystems will increasingly focus on their specialties due to cognitive limits. The matching process will produce distinct groups of the members who tend to work on a specific component of the whole product, thus the organizational structure will become more modular. Therefore we have the following:

Hypothesis 1: The modularity of an organization is positively related to the number of modules of its product.

In our conceptualization, modularity is a continuum, thus the more members are specialized and engage in division of labor, the more modular is the organization structure. We believe the size of contributors could be another important diver for modular organization. When an organization is small, its structure can be simple, and it may not even have a formal structure. However, increased number of contributors can potentially cause two problems: communication and coordination. As number of contributors increase, the messages to be exchanged will increase exponentially. However, over-communication can potentially cause misunderstanding, redundant information, and communication congestion, thus negatively affect performance. By adopting modular organization, where communications tightly related will be restricted inside an organizational module or unit, and communications loosely coupled will be exchanged across different modules through their interface, the communication within the organization will be more effective. Second, as contributors grow, their knowledge base gets increasing complicated and their tasks get highly specialized. A modular organization is necessary under this circumstance to coordinate their activities both within and across different expertise areas. A modular design allows organizations to balance the need for simultaneous centralization, decentralization and coordination, and can potentially results in fast responsiveness to dynamic environments (Lei, Hitt and Goldhar, 1996). Summarizing the above, as the number of contributors increase, modular organizational design is needed to maximize specialization and improve efficiency. Thus we have:

Hypothesis 2: The modularity of an organization is positively related to the size of contributors.

However, the concept of organizational modularity should not be a static one, particularly over different stages of the product development life cycle, which typically goes through a cycle from conceptual design stage to mass production stage. The conceptual design of heavily engineered products demands flexible, highly interactive organizational set-ups, wherein the related and numerous engineering disciplines can interact and cross-fertilize (Brusoni and Prencipe, 2001; Langlois, 2002; von Hippel, 1990). So in this stage, organizational structure that is too much modular might be actually counter-productive. On the other hand, when product design has been finalized and needs to be implemented into specific product form, the division of labor and knowledge can more effectively leveraged, so that individuals can specialize in their own functional areas. Thus we have:

Hypothesis 3: Organization tends to be less modular in the early stages of its life cycle than in later stages.

RESEARCH SETTING, VARIABLES, AND ESTIMATION MODELS

To empirically test the hypotheses, we make use of the open source software (OSS) development data hosted by SourceForge, the world's largest OSS project hosting website. While the principle of modularity was initially confined to the physical components of products like automobiles or stereos (e.g., Langlois and Robertson, 1992; Ulrich, 1995), today it is

also applied to less tangible components like software modules or even to intangible objects like basic scientific and technological knowledge (e.g., Arora et al., 1997; Fixson, 2007).

Code modularity is particularly important for OSS development since it allows allocating tasks among geographically distributed programmers. As a matter of fact, many of the OSS programs, e.g., Sendmail, Samba, Mozilla, and even Linux, have been rewritten in a modular architecture to ensure successful development (Baldwin and Clark, 2006; Fitzgerald, 2004). In OSS, programmers either are assigned or choose to code the individual code modules. If each programmer codes only one module, then the organizational structure of the software development team is highly modular. This is equivalent to the cases where a whole product is decomposed into several components and then each component is produced by different and non-overlapping manufacturers, resulting in a loosely coupled production arrangement (Schilling, 2000). In contrast, if many of the programmers concurrently code several modules, the organizational structure will be less modular. This is illustrated in Figure 1: both the left and the right panel has six programmers, P1-P6, and three software modules, m1-m3. In the left panel each programmer codes only one module, thus the organizational structure of the team is highly modular. In contrast, in the right panel, three of the programmers, P1, P3, and P5, code all three modules simultaneously, thus the structure of the team in the right panel is less modular.
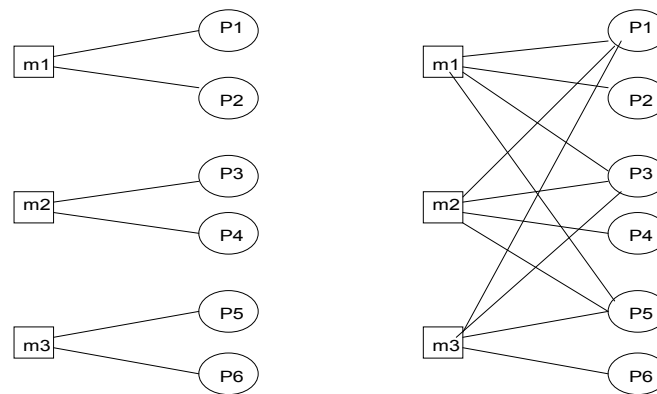

Figure 1. Code Modularity for OSS Development Illustration

To avoid left censoring problem, we restrict our samples to Java foundry project registered on and after January 1, 2003, and we observe the complete coding history for each of these projects until May 2006. At SourceForge, a foundry represents a technology that is shared by a group of projects, thus it is a subset of the whole projects hosted by SourceForge. For each of the project, we identify the number of modules, the age of the project (in months), the programmers in each project, and coding activities of each programmer, as well as other project characteristics such as intended audience, operating systems, and project topics. Further we restricted our sample to those projects that have at least 2 programmers on the project team.

To calculate the dependent variable, organizational modularity, we first trace for each of the programmers the total number of modules (s)he contributed to, and then divide it by the total number of module in the projects, i.e., we calculate $c_{ij} = m_{ij} / m_j$, where m_j is the total number of modules for project *j*, and m_{ij} is the total number of modules that has been contributed by programmer *i* for project *j*. Then we calculate the dependent variable as $modularity_j = 1 - (\Sigma c_{ij} / N_j)$, where N_j is the total number of programmers for project *j*. It can be verified that $modularity_j$ falls between 0 and 1, and the higher the value, the more modular the project structure. Variable *modules* is the total number of project modules for each project divided by 100, and it is used to test Hypothesis 1. Variable *programmers* is the total number of programmers on a project, and it is used to test Hypothesis 2. Finally variable *age* measures the months elapsed since the project registered with SourceForge till May 2006 divided by 10, i.e., *age* is used to approximate the development stage of the product so to test Hypothesis 3. We estimate all hypotheses using OLS model.

ESTIMATION RESULTS

We present the descriptive statistics and the correlation matrix of key variables in Table 1. From the correlation matrix, we can see that modularity is positively correlated with the other independent variables and these patterns are largely consistent with our hypotheses.

Table 1. Descriptive Statistics and Correlation Matrix

Variables	Mean (s.d)	1	2	3	4
1. Modularity	0.151 (0.247)	___			
2. Modules	0.350 (0.552)	0.410***	___		
3. Programmers	3.751 (2.94)	0.734***	0.413**	___	
4. Age	3.352 (0.708)	0.054**	−0.002	0.038	___

Note: N =1,728. ** *p*<0.05, ***p*<0.01.

We test for multicollinearity among the independent variables in all the OLS models. This is done by calculating the variance inflation factor (VIF) for all the independent variables. In all the models, the individual VIF values are all well below the threshold of 10. Consequently, multicollinearity should not be a problem in our specifications (Neter, Kutner, Nachtsheim and Wasserman, 1996). We also test for heteroskadasticity in our models, and the results do not show serious heteroskadasticity in the models.

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The results for Hypotheses 1 to 3 are provided in Table 2. Model 1 only has the three key independent variables. Model 2 includes all the control variables, i.e., the 19 dummy variables for intended audience, operating systems, and topics. In both models, the coefficients on modules and programmers are positive and highly significant, while the coefficient on age is marginally significant. Therefore, all three hypotheses are supported.

Table 2.   Estimation Results

Independent Variables	Model 1	Model 2
Modules	0.057*** (0.019)	0.055*** (0.008)
Programmers	0.087*** (0.002)	0.86*** (0.002)
Age	0.010* (0.06)	0.013** (0.06)
R^2	0.556	0.572

Notes: N=1,728. Dependent variable is organizational modularity. **p*<0.05, ***p*<0.05, ****p*<0.01. Model 2 include other control variables like intended audience, operating systems, and topics.

CONCLUSION

In this study, we examine whether and how modular products lead to modular organizations under the setting of OSS development. We contribute to this important literature by looking into the black box of development processes of software product. Our results support and extend the view that there indeed exists a one-to-one mapping between product and organizational modularity. There are several future research directions for this research. First, our analysis is conducted at team level. Though many results at team level apply to organizational level, empirical evidence at organizational level are encouraged so to provide direct support to our hypotheses. Second, OSS is public goods and a free product; therefore, future studies may want to examine the cases where organizations are designed to produce commercial products.

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