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2006/43/TOM/OB

# Component Modularity, Team Network Structure and the Attendance to Technical Interdependences in Complex Product Development

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We appreciate the assistance of the engineers at Pratt & Whitney Aircraft for their collaboration during the data collection of this study. We also appreciate the comments from participants in the innovation forum at the Carnegie Bosch Institute conference (Stuttgart, Germany, Fall 2005) and the Wharton Technology mini-conference (April, 2006). We are grateful for insightful comments of Jonghoon Bae, Steven Eppinger, Gokhan Ertug, Christoph Loch, and Luk Van Wassenhove. We also appreciate the support of the INSEAD/Wharton Alliance Center.

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## Abstract

The development of complex products poses substantial operational and organizational challenges to established firms. Previous research has shown that coordinating technical interdependences is vital for the successful development of complex products. We integrate research streams in product development and organizational theory to study the determinants of the ability of teams to attend to technical interdependences in complex product development projects. We hypothesize that components' attributes, such as modularity and redesign, and teams' communication network structure significantly influence their attention to technical interdependences. We test our hypotheses by examining the network of components of a large commercial aircraft engine and the technical communication network structure of the organization that designs it. Our findings suggest that although teams' communication network structure plays a critical role in the capability of teams to attend to interdependences, its impact is moderated by the modularity and redesign of product components.
**Keywords**: Product Architecture; Modularity; Organization Design; Social Networks; Structural Holes.

## 1. Introduction

The development of complex products poses substantial operational and organizational challenges to firms. Organizations have developed two complementary approaches to deal with such challenges. The operational approach decomposes complex products into systems, which may be further decomposed into smaller components if they are still deemed too complex (e.g., Alexander 1964, Simon 1981, Suh 2001). Such an approach determines the architecture of the product, which is defined by the way components interface with each other so that the product can fulfill its functional requirements (Ulrich 1995, Ulrich and Eppinger 2004). The organizational approach assigns each component to a team responsible for its design and for its integration with other components to ensure product functionality (e.g., Clark and Fujimoto 1991, Robertson and Allen 1992, Terwiesch et al. 2002). When developing products, design interfaces among product components typically determine technical interdependences among design teams. Therefore, effective coordination across interdependent teams is one of the most critical challenges for successful complex product development (Thompson 1967, Galbraith 1973, Smith and Eppinger 1997, Mihm et al. 2003).

While coordination among interdependent teams is crucial for successful product development, teams typically “ignore” (or pay marginal attention to) a number of interdependences during the development process (Sosa et al. 2004). Some level of neglect is perhaps unavoidable given the cognitive and resource limitations typically faced by teams (Simon 1947, Ocasio 1997). Yet, unattended interdependences can at times result in substantial costs for firms. For example, Henderson and Clark (1990) found that in the semiconductor photolithography alignment equipment industry novel interfaces between existing components were often neglected by design teams, causing established firms to lose their leading position in the market. In our research site, several critical design interfaces were not attended to by the corresponding design teams during the design phase, some of which resulted in increased development costs and delays. One of the unattended interfaces, for example, “caused excessive loads on assembled hardware in early development tests, resulting in severely distressed hardware and special disassembly procedures”; another unattended interface “also caused excessive loads and reduced life to a critical engine component, but was not discovered until the first engines entered service" (Sosa et al. 2004: 1687).

Paradoxically, little is known about the factors that affect the capability of teams to effectively attend to their interdependences[2]. This is the topic addressed in this paper. What drives the capability of teams to attend to their technical interdependences? Is it the product architecture, the organizational structure, or both? Building on existing research in product development (e.g., Ulrich 1995, Krishnan and Ulrich 2001) and in social network theory (e.g., Coleman 1988, Burt 1992, Gargiulo and Benassi 2000), we argue that both product architecture and the structure of the team's communication network can facilitate (or hinder) the team's ability to coordinate with other teams in the development process. Specifically, we focus on how the structure of a team's technical interdependences, as determined by the product architecture and the degree of product redesign (relative to previous product generations), and the structure of the team's communication network affect its attention to those interdependences.

Research in product development has mostly focused on understanding the structure of the development process and its impact on the organization. A stream of work focuses on minimizing and identifying the set of activities that are more likely to iterate and create rework so that they are managed with special attention (e.g., Steward 1981, Eppinger et al. 1994, Smith and Eppinger 1997, Mihm et al. 2003). The minimization of interdependences is central to the notion of "modularity," which focuses on reducing the connection across sets of physical components, development activities and/or organizational teams (e.g., Ulrich 1995, Baldwin and Clark 2000). Product modularity has been associated with flexibility to adapt and generate product variety (Ulrich 1995). Product modularity also facilitates the evolution of designs and industries by allowing teams to work independently on loosely coupled problems (Baldwin and Clark 2000). In the process domain, modularity has been proposed as a mechanism to reduce cost in design testing and to mitigate design oscillations in complex engineering projects (Loch et al. 2001, Mihm et al. 2003). In the

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[2] We broadly follow the definition of *attention* provided by Ocasio (1997: 189) who defines it as "the noticing, encoding, interpreting, and focusing of time and effort by organizational decision-makers on both (a) *issues*... and (b) *answers*." Hence, in the context of this paper, attention happens when design teams identify a design issue between the components they develop and interact about it.

organizational domain, modularity has also been proposed as a source of flexibility to the organization (e.g., Sanchez and Mahoney 1996, Schilling 2000, Ethiraj and Levinthal 2004). Previous work in product development has also considered the dynamic nature of design tasks across product development projects, recognizing that not all technical interdependences are equally novel to the team, as complex products are typically a mix of new and redesigned systems (Henderson and Clark 1990, Terwiesch et al. 2002, Clarkson et al. 2004). Regardless of its focus, the research in product development has coincided with earlier studies in R&D teams (e.g., Allen 1977, Brown and Eisenhardt 1995) in assuming that intense communication is necessary to execute highly interdependent design tasks. The higher the interdependence, the higher the coordination needs and the more intense the communication needs.

The organizational literature inspired in social network theory has been mostly concerned with how communication networks can help or hinder an actor's ability to coordinate with other interdependent entities. A substantial body of evidence suggests that this ability is enhanced by access to non-redundant information and by the flexibility to adapt behaviors to changing needs, which are associated with large and sparse communication networks (Burt, 1992, 1997; Gargiulo and Benassi 2000; see Burt 2000, for a comprehensive review). More recently, however, scholars have stressed that lack of mutual trust and fear of opportunism typically associated with sparse communication networks (Coleman, 1988, 1990) may mitigate—and even reverse—the benefits of such networks on performance. This observation has led scholars to propose that the relationship between network structure and outcomes should be contingent on task characteristics. The more collaboration among actors is essential for task outcomes, the less likely that sparse network structures would be positively associated with such outcomes (e.g., Ahuja 2000; Obstfeld 2005).

In this paper, we build on these different literature streams to offer three important contributions. First, we take a network analytical perspective to integrate product development and organizational theories to explain a phenomenon that is equally important for both fields—namely, how product structure at the component level and informal communication structure at the team level affect the capability of teams to attend to technical interdependences in complex product development. Second, we propose a network analytical approach to measure the degree of modularity of a given component based on the extent to which a component is strongly interdependent with other components that are also interdependent. Third, and more importantly, we propose and show that in complex products with a mix of novel and reused components, a sparse communication network significantly influences the ability of teams in charge of a specific product component to attend to their technical interdependences, yet such an effect is mitigated by the degree of modularity and redesign (from prior generations) of that component.

## 2. Framework and Hypotheses

A complex product can be conceived as a network of components, with each component being a "node" and the interfaces between components being the "edges" (or ties) of the network. Similarly, the interactions among teams responsible for designing or for integrating such components can be viewed as a social network, with the teams being the nodes and the technical communication between them the edges of the network. Theoretically, an identified interface between two components should trigger some interaction between the teams in charge of those components. In some cases, however, team interactions might also trigger the establishment of new interfaces between components. Yet some interfaces may not be properly identified in the product architecture, and not all teams whose components are linked through an identified interface actually interact during the project implementation phase (Henderson and Clark 1990, Sosa et al. 2004).

Superimposing the network that maps the interfaces that define the product architecture onto the network that portrays the observable technical interaction structure of the design and integration teams, one can identify five types of interdependences between teams (Figure 1). First, *attended interdependences* occur when a design interface between two components is identified and the teams designing those components interact about it (interdependences *a*, *b* and *c* in Figure 1). Second, *unattended interdependences* occur when a design interface is identified and the corresponding teams do not interact (interdependence *d*). Third, *unidentified interdependences* happen when the teams interact (for technical purposes) but no design interface between them has been identified by system architects (interdependence *e*). Fourth, *lack of interdependence* occurs when there is neither design interface nor team interaction such as the lack of ties between teams 2 and 4 in Figure 1. Finally, *external interdependences* occur when teams which are not directly responsible for the design of a component interact with teams designing components. This may be the case with teams that are in charge of overseeing the integration among different aspects of the design but are not responsible for designing any specific component, as is the case with teams 5 and 6 in Figure 1.

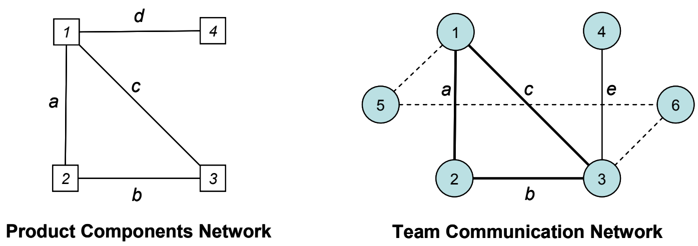


**Figure 1. Hypothetical networks of components and teams**

Prior research in product development has used a network analytical approach to examine the architecture of complex products (Sosa et al. 2003, Sosa et al. 2005) and to study the factors that explain the existence of unattended and unidentified interdependences in design organizations (Sosa et al. 2004) [3]. In the organizational theory domain, Gargiulo and Benassi (2000) have shown how the structure of an actor's communication network can affect this actor's ability to coordinate interdependences. In this paper, we study how the "modularity" and "redesign" of each component and the structure of the design team's communication network affect the team's ability to attend to its technical interdependences.

## Effects of component modularity and redesign

We take a resource utilization perspective on complex product development (Adler et al. 1995) to study the effects of component modularity and component redesign on teams' attention to their technical interdependences. From this perspective, teams are considered as "workstations" responsible for designing a physical or functional component of the product, and a team's workload is largely

[3] Note that the focus and unit of analysis of this paper differ significantly from Sosa et al. (2003, 2004). In this paper the unit of analysis is the team and component, while the unit of analysis in Sosa et al. (2003, 2004) is the interdependence itself. As a result we study here how network structures of components and teams affect the ability of teams to coordinate with other teams in a complex product development effort. As for Sosa et al. (2005), such a paper defines component modularity based on the notion of centrality (Freeman, 1979), which is different from the definition we operationalize in this paper based on the notion of constraint (Burt 1992).

determined by the characteristics of the component it designs. The capacity of the team to process its workload determines the team's "delay" in attending to the next "job" in the design task list (Jackson 1957). Hence, the busier the team is, the longer design tasks "wait" to be processed, and the lower the probability that the team will be able to attend to all its technical interdependences [4].

Two important properties of a component determine the workload of the team designing that component: modularity and redesign. Component modularity is the main structural property that captures the connectivity of the component with other components in the product. Component redesign captures the novelty of the component relative to previous versions of this same component in older product generations. We discuss the effects of these two properties on a team's ability to attend to its technical interdependences in the following paragraphs.

*Component modularity.* The common notion in this line of research is that modularity decouples otherwise interdependent groups of elements. Decoupling of elements generates flexibility to adapt to changes. Modular products are easier to change and upgrade, facilitating product variety (Ulrich 1995). In the process domain, modular development processes are less prone to design iterations and rework (Smith and Eppinger 1997, Mihm et al. 2003). In addition, the work structure associated with modular components is less complex, which reduces the effects of ambiguity and uncertainty in development projects (e.g., Pich et al. 2002, Ethiraj and Levinthal 2004).

Since complex products are hierarchically decomposed into systems and components for design purposes (Simon 1981), we can define modularity at the product, system and component level. Modular products include a one-to-one mapping of product functions to product components, resulting in "decoupled interfaces between components" (Ulrich 1995: 422). Within the product, previous research has focused on how systems (i.e., groups of components) share interfaces with other systems (without explicitly considering how components interact within systems). As a result, modular systems are defined as groups of components whose interfaces are clustered among few adjacent systems (Sosa et al. 2003). Finally, modularity can be also defined at the level of the

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[4] Queuing theory (e.g., Jackson 1957) shows that the delay in processing a design task increases exponentially with the utilization rate of the team (i.e., the workload/capacity ratio).

components within a product as "the level of independence of a component from the other components in a product" (Sosa et al. 2005: 3). Building on such a general definition, we operationalize component modularity as *the degree to which a component lacks direct and indirect interfaces with other components in the product*. From a network analytical perspective, a modular component has fewer and weaker direct and indirect links (technical interfaces) with other components within the product. As such, modular components are less "connected" with other components and can be viewed as more flexible from a product design perspective (Suh 2001). It is important to emphasize that since our unit of analysis is the component (and the team that designs it), we focus on modularity at the component level rather than at the system or product level.

The relative independence of modular components makes them less likely to generate highly coupled design tasks, which are the primary source of rework and iterations during the development process (Smith and Eppinger 1997, Mihm et al. 2003). The more "modular" a component is, the more likely it is to generate a predictable workload structure (Ulrich 1995, Sanchez and Mahoney 1996, Baldwin and Clark 2000, Loch et al. 2001). Because component modularity reduces task complexity, teams responsible for highly modular components should have more spare capacity, all else being equal, to handle their design interfaces, which should then increase their ability to attend technical interdependences. Conversely, teams in charge of components that lack modularity due to their tight integration with many other components in the system should have less spare capacity to handle design interfaces, making them less able to attend technical interdependences.

While the negative effect of low component modularity on a team's ability to attend to technical interdependences may be in part compensated with assignment of additional engineering resources, the effects of low modularity often go beyond the interfaces with adjacent components, making it difficult to adequately assess *a priori* the effects on team workload (Pich et al. 2002, Mihm et al. 2003, Clarkson et al. 2004). Because teams in charge of modular components face a more predictable workload, whereas teams responsible for non-modular components are more likely to confront unforeseen design interactions that strain the team resources, we expect that, controlling for such resources, component modularity should have a positive effect on the team's ability to handle technical interdependences. Hence:

*H1: Component modularity is positively associated with the design team's attention to technical interdependences.*

*Component redesign.* Another important component characteristic that could affect the capability of a team to attend to its interdependences is the degree to which the specific component changes relative to a previous generation of the same product. We call this "component redesign."[5] Complex products typically contain a mix of novel and reused components (e.g., Robertson and Ulrich 1998, Fisher et al. 1999). Redesigned components (with a low percentage of carryover from previous product generations) can be found even in derivative products that belong to the same platform and reuse the same product architecture, since some components may need to be redesigned in order to adapt the derivative product to its new functional requirements (Ulrich and Ellison, 1999).

From a resource utilization perspective, component redesign can put a heavy burden on the team responsible for the specific component, straining the team's resources and leaving less spare capacity to coordinate interfaces with other design teams. Component redesign would typically focus a team's resources on its own component and away from the interfaces with other components. At the same time, redesign may also create, remove or alter design interfaces with other components, which increases the uncertainty of such interfaces. While increasing uncertainty should result in higher attention to the changing interfaces (Galbraith 1973), the lack of spare capacity may actually make the team *less* likely to attend to such interfaces (e.g., Adler et al. 1995, Henderson and Clark 1990). The appearance of the jet engine provides a vivid illustration of this phenomenon. Firms in the aircraft industry realized that they needed to focus on developing jet engine expertise, but they failed to pay sufficient attention to how the introduction of the jet engine "would change the interactions between

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[5] Here we refer mainly to intended or planned changes in product components to fulfill new functional requirements or adapt to a new product configuration, rather than changes due to unplanned design rework ocurring during the development process.

the engine and the rest of the plane in complex and subtle ways" (Henderson and Clark 1990: 17, Gardiner 1986).

Managers, again, are likely to consider the additional workload when assigning engineering resources to teams engaged in component redesign, in the same way they take into account the modularity (or lack thereof) of the specific component. The increasing uncertainty in the interfaces between the redesigned component and other components in the product, however, makes it intrinsically difficult to adequately and accurately allocate resources to teams redesigning a component (Terwiesch et al. 2002). Moreover, additional resources may not be sufficient to counteract the tendency of the team to focus on the design of the component itself, neglecting the effect that redesign might have on the novel interfaces. Thus, we expect that the amount or level of component redesign should result in a direct negative effect on the team's ability to attend to its technical interdependences:

*H2: Component redesign is negatively associated with the design team's attention to technical interdependences.*

**Effects of the communication network structure**

In addition to the effects that component modularity and redesign may have on the team's capacity to process its workload and thus on its ability to attend to its technical interdependences, organizational theory suggests that such ability may be also affected by factors related to the team's informal communication network with other teams in the design process. Study of the effects of communication networks on team performance is a long tradition in organization research, dating back to early studies of R&D organizations that associated both intense and cohesive internal communication with high-performing organizations (Allen 1977) while also recognizing the critical role of "boundary spanners" (Tushman 1977) in linking the team with the rest of the organization. More recently, the emphasis on the role of communication networks—and network structure in particular—on team performance has gained increasing attention from scholars using social network analysis to study how the structure of a team's communication network can affect its performance (e.g., Reagans and Zuckerman 2001). Building on social network analysis, we argue that the ability of a team to attend to technical interdependences can be affected by the social structure of the communication network among the various teams involved in the design of the product.

Structural holes theory (Burt 1992, 2004) proposes that sparse networks lacking connections among an actor's contacts—that is, networks rich in "structural holes"—maximize the actor's access to non-redundant information and creation of innovation brokerage opportunities (Hargadon and Sutton 1997). Because information circulates through communication ties between actors, it is typically more homogeneous within closely connected clusters than between disconnected clusters. A team that communicates with a small number of other teams that also communicate with each other is likely to receive similar—i.e., "redundant"—information through multiple channels. In addition, the amplification of the signal that results from receiving similar information through multiple channels is likely to increase the likelihood that the team would ignore, disregard or fail to seek information coming from outside the cluster. Conversely, a team that is connected to a number of other teams not connected to one another should have better access to non-redundant information on product-related issues (Burt, 2004). Sparse communication networks are also likely to increase the flexibility of a team to focus its attention where it is most needed. In a study of managers coordinating project teams in an information technology firm, Gargiulo and Benassi (2000) showed that managers whose communication networks were rich in structural holes were less likely to fail to coordinate emerging task interdependences.

The superior access to non-redundant information on the events that occur throughout the development effort, and the greater flexibility to refocus their attention, should make teams with networks rich in structural holes more likely to know how to direct their efforts towards the relevant component interfaces, which should increase their ability to attend to their technical interdependences. Conversely, teams whose communication networks span few structural holes should more likely to miss out (or neglect to pay sufficient attention to) events that can affect the interfaces with their own component, which should decrease their ability to attend to their interdependences. Therefore,

*H3: A team's communication network rich in structural holes is positively associated with its attention to technical interdependences.*

While *H3* highlights the information and flexibility benefits of sparse communication networks, such networks can also entail costs that, in some circumstances, may mitigate—or even reverse—the purported benefits. Researchers that focus on the effects of networks on the production of social norms that facilitate communication and trust between actors have stressed that collaboration is more likely to occur in thick relationships embedded in common third parties, and thus it should be less likely to emerge in sparse networks. Members of a closely knit network are more likely to trust and to understand each other, diminishing the uncertainty of their exchanges and enhancing their ability to collaborate toward solving common problems (Granovetter 1985, Raub and Weesie, 1990). Building on these insights, Rowley, Behrens and Krackhardt (2000) argue that sparse networks may be detrimental for organizational performance in task environments where exploitative activities are more important than explorative activities, whereas Bae and Gargiulo (2004) show that although firms with sparse alliance networks capture superior value from collaboration, such networks decrease the benefits for firms linked to non-substitutable (i.e., highly dependent) alliance partners. In a similar vein, Ahuja (2000) suggests that when developing a collaborative milieu and overcoming opportunism are essential to success, densely connected networks are likely to be more beneficial than networks rich in structural holes. This is consistent with Obstfeld (2005), who found that dense social networks and a willingness to "close" structural holes were significant predictors of innovation involvement. A common theme in these studies is that the effect of network structure on outcomes may be contingent on task characteristics.

**Contingencies of team network structure**

The joint consideration of the costs and benefits of sparse networks, and the possibility that such costs and benefits may vary across tasks, opens the way to consider that the effects of team network structure may be contingent on the nature of the task confronting the team. The moderating effect of task characteristics can operate through two different mechanisms. First, task characteristics may make flexibility and access to non-redundant information less consequential for the team's ability to attend to technical interdependences, hence diminishing the benefits of sparse networks. Second, task characteristics may make the team's attendance to interdependences dependent on the collaboration with adjacent teams, which may be hindered in sparse network structures (e.g. Ahuja, 2000; Ostbfeld, 2005)

In our study, both component modularity and component redesign are two important determinants of task characteristics that may mitigate the effects of a network structure rich in structural holes on a team's ability to attend to interdependences. Since modular components are more independent from other components, their design teams are less affected by actions taken by other teams in the development process. By definition, teams in charge of modular components have fewer direct and indirect interfaces with other teams in the development process. Hence, teams in charge of modular components are less likely to benefit from non-redundant information about a large and a diverse number of components, which is typically associated with communication network rich in structural holes. In addition, maintaining communication networks rich in structural holes requires an investment of time and energy by the team members. If the information accessed through that network is not relevant for the task—as is the case for teams designing modular components—such an investment is likely to strain team resources without corresponding benefits. The volume and the diversity of information exchanged in a large and sparse network may also impair the focal team's ability to concentrate on the few interfaces that really matter for its modular component, impairing its ability to attend to technical interdependences.

Teams in charge of modular components are also less likely to benefit from having the flexibility to adjust communication efforts that are typically associated with networks rich in structural holes (Gargiulo and Benassi 2000). Indeed, the flexibility provided by the communication structure is less relevant when designing modular components, because these components already provide a more stable and flexible task structure associated with fewer and less uncertain design iterations (Smith and Eppinger 1997, Loch et al. 2001, Mihm et al. 2003). Hence, a team designing a modular component with a large and sparse communication network rich in structural holes is likely to over invest in communication in relation to the needs stemming from its task characteristics without obtaining tangible benefits from such an investment. Therefore, we expect that the benefits associated with communication networks rich in structural holes will be less apparent for teams designing highly modular components:

*H4: Component modularity mitigates the effect of networks rich in structural holes on a teams' attention to technical interdependences.*

The effect of a communication network structure rich in structural holes may be also mitigated for teams engaged in high levels of component redesign. The lack of component design carryover from the previous product generation introduces a fundamental change in the task environment of a team. When there is mix of reused and novel components in a complex product, an important coordination challenge for teams is to determine which interfaces require more attention. Designing a highly novel component poses different communication needs than designing a component with high percentage of carryover. Teams handling components with low redesign content are typically charged with maintaining their performance specifications while minimizing the changes to their component. Hence, they are inherently more externally focused on the interfaces. Because the main challenge for these teams is to discover what interfaces may require attention due to changes originated in (or caused by) other components, they can benefit from a sparse communication network that maximizes the access to non-redundant information on the whole development effort.

A team that is engaged in a substantial redesign of its component may need to minimize the risk of being too internally focused and overlooking interfaces that require attention and direct coordination with other teams (Henderson and Clark 1990). Holding modularity constant, the importance of managing interfaces increases with the level of component redesign. In this context, the team would benefit most from collaborative communication among other teams, which is favored by a closely knit network. Such network would make it more likely that adjacent teams would help steer the attention of the redesigning team away from its own novel component and toward the interfaces that really matter, as opposed to focusing only on its component or expending energy on interfaces that don't count (Obstfeld 2005). Thus, we expect that teams in charge of components with substantial redesign relative to prior generations will derive some benefits from the collaborative environment prompted by small, closely-knit networks. Because such an environment is less likely to emerge in sparse networks rich in structural holes, we expect that component redesign will mitigate the net effect of networks rich in structural holes on the team's attention to technical interdependences:

*H5: Component redesign mitigates the effect of networks rich in structural holes on a teams' attention to technical interdependences.*

## 3. Data and Methods

We test our hypotheses by studying the detailed design phase during the development of a large commercial aircraft engine at Pratt & Whitney, the PW4098 that equips the Boeing 777 two-engine aircraft. Several factors justified the selection of the project to study. First, the project was a complex design that exhibited explicit decomposition of the engine into systems, and these into components. Second, the assignment of a single development team to each component facilitated the implementation of our research approach. Third, the model studied was the most recent engine program to complete design and development, and almost all team members involved in the detail design development phase were still accessible. Finally, the derivative engine studied was part of a family of large commercial engines and had about 40% of design content carried over from the previous model. In addition, two new derivative engines, whose development could gain directly from this study, were already planned.

We captured the technical interface network of the 54 components that comprised the engine and the communication network of 60 teams (54 design teams and 6 integration teams) that developed the engine components and evaluated the overall engine performance (see Sosa et al. 2003 and Sosa et al. 2004 for details). We collected data from multiple sources. Product network data was obtained by interviewing several experienced engine architects. Data on communication among teams was gathered by interviewing and surveying key members of design teams using standard sociometric questions (Marsden 1990). We also gathered from each design team member surveyed data about the level of carryover of the engine component he or she designed. By gathering data from multiple sources we reduced the effect of single-source bias (Podsakoff and Organ 1986). In addition, the use of multiple individual responses and multiple data sources to construct the network variables minimized the effect of response bias when testing our network hypotheses.

**Product network data**

Our data capture both the breakdown of the engine structure into eight systems and 54 components and five types of design dependencies among those components: spatial constraint, structural constraint due to transfer of loads, exchange of material, exchange of energy and exchange of information. As a result, a design interface between component *i* and *j*, $m_{ij}$, comprises five types of design dependencies, $x_{ij,type}$, where type is either spatial, structural, material, energy or information dependency. Each design dependency type was coded to be either weak ($x_{ij,type}$ = 1) or strong ($x_{ij,type}$ = 2), depending on the impact on functionality of component *i* due to its dependency with component *j*. (See Sosa et al. 2003 and Sosa et al. 2005 for details.)

Since we are interested in capturing identified technical interdependence between components, we measure the existence of a design interface between any two components. The design interface between components *i* and *j* is the sum of their design dependencies due to spatial, structural, material, energy and/or information functional requirements in both directions, standardized by the maximum overall design interface detected between any two components in the engine. The standardized design interface between components *i* and *j* is calculated as follows:

$$m_{ij} = \frac{\sum_{type} x_{ij,type} + \sum_{type} x_{ji,type}}{\max(\sum_{type} x_{pq,type} + \sum_{type} x_{qp,type})}, \qquad i \neq j ; \quad p \neq q; \quad p=[1, Num.\ of\ comps.]; \quad q=[1, Num.\ of\ comps.]$$

Our measure of design interface yields a valued symmetric network of product components where $0 \leq m_{ij} \leq 1$, with reciprocal design dependencies producing comparatively stronger technical interdependences. We found eight distinct pairs of components whose design interface reached the maximum design interface strength ($m_{ij}$ = 1). Figure 2 shows a cross-sectional view of the engine studied as well as the network diagram of the 54 components of the engine. The nodes are colored to illustrate the eight systems that comprised the engine: Fan, Low-Pressure Compressor (LPC), High-Pressure Compressor (HPC), Combustion Chamber (CC), High-Pressure Turbine (HPT), Low-Pressure Turbine (LPT), Mechanical Components (MC) and External and Controls (EC).

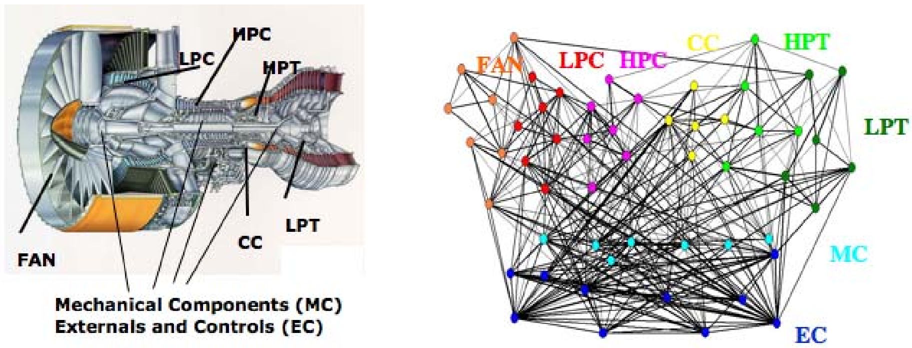


**Figure 2. Cross-sectional view and network diagram of the PW4098 aircraft engine**

**Communication network data**

The teams' communication network is defined by the intensity of their technical interactions with other teams during the project. We measure the intensity of the interaction of team $i$ with team $j$, $z_{ij}$, using a discrete scale that considers both the frequency and impact of the information requested by team $i$ from team $j$[6]. Because we were interested in capturing the total interaction between teams, we followed Burt (1992) and measured team $i$'s communication with team $j$, $p_{ij}$, as the proportion of time and energy team $i$ has to allocate to team $j$, both as a result of $i$'s seeking out $j$ ($z_{ij}$) and of being sought out by $j$ ($z_{ji}$):

$$p_{ij} = (z_{ij} + z_{ji}) / \sum_{i \neq q} (z_{iq} + z_{qi}), \qquad i \neq j;\ q=[1, Number\ of\ teams]$$

The expression above takes into account the total interaction between teams $i$ and $j$ to calculate the strength of their communication. However, it maintains the asymmetry of the tie insofar as the denominator $\sum_i (z_{iq}+z_{qi})$ varies across teams. If team $i$ communicates with many different teams (including $j$) whereas team $j$ interacts with only a few teams, their communication will be less salient

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[6] Our *interaction intensity* measure ($z_{ij}$) captures both interaction *criticality* (routine: the information requested was important but could be generated by the team alone with minimal risk of delay; important: the information requested could be generated by the team alone with some risk and effort; critical: the information could not be generated by the team alone) and interaction *frequency* (very frequent: daily or almost daily; frequent: weekly or biweekly; infrequent: monthly or less; never). Hence, non-zero interaction intensity ranges from "routine and frequent" to "critical and very frequent." We excluded interactions that were routine AND infrequent because they were likely to be spurious or redundant information exchanges. After follow-up interviews to validate our communication data, we also excluded interactions that were social or consultative in nature. Hence, we exclusively captured relevant technical interactions related to the design of the engine.

for $i$ than for $j$ and $z_{ij} < z_{ji}$. Note that out of 1,770 potential communication ties among the 60 design teams 443 interactions were observed, corresponding to a communication network density of .25.

**Classifying technical interdependences**

We classified technical interdependences considering both the existence of a design interface between components as determined by the product architecture and the existence of communication between the respective design teams. To do this, we compared the network of technical interdependences with elements $m_{ij}$ with the communication network with elements $p_{ij}$ for the 54 design teams directly responsible for components. Although interactions with the six integration teams was retained to determine the social structure of the communication network around a design team, we did not consider these interactions when classifying technical interdependences between teams because there were no design interfaces between integration and design teams. This allowed us to identify four types of technical interdependences between teams $i$ and $j$:

If $m_{ij} > 0$ AND $p_{ij} > 0$ then there was an *attended interdependence* between teams $i$ and $j$

If $m_{ij} > 0$ AND $p_{ij} = 0$ then there was an *unattended interdependence* between teams $i$ and $j$

If $m_{ij} = 0$ AND $p_{ij} > 0$ then there was an *unidentified interdependence* between teams $i$ and $j$

If $m_{ij} = 0$ AND $p_{ij} = 0$ then there was a *lack of interdependence* between teams $i$ and $j$

We then calculated the counts of each type of interdependence for the 54 teams. Figure 3 reports the number of cases for each type of interdependence for the 1,431 pairs of components and teams.

It is worth noting that this classification yields 46 cases of communication between design teams that do not correspond to interfaces identified in the product architecture. We labeled these cases "unidentified" interdependences to signal the fact that they were not directly linked to a design interface identified in the product architecture. There are two alternative interpretations for unidentified interdependences. A first interpretation would treat communication in the absence of an identified design interface as spurious or redundant interdependence. However, because we inquired specifically about communication that was directly related to the technical aspects of the project and that could have an impact on the work of the requesting team, unidentified interdependences were most likely the result of interfaces between components that were uncovered during the execution of the project (Sosa et al. 2004).

| | | | |
|---|---|---|---|
| **Team Interactions ($z_{ij}$)** | NO (1,149) | **117 Unattended Interdependences** | 1,032 Lack of Interdependences |
| | YES (282) | **236 Attended Interdependences** | **46 Unidentified Interdependences** |
| | | YES (353) | NO (1,078) |
| | | **Design Interfaces ($m_{ij}$)** | |

**Figure 3. Four types of technical interdependences**

**Dependent variable**

Our dependent variable is the extent to which teams were able to attend to their technical interdependences. We measure this variable as the sum of attended and unidentified interdependences of each team divided by the total number of interdependences affecting the team (unattended, attended and unidentified). This definition accurately captures the total attention to interdependences (numerator) over total number of interdependences (denominator).

**Independent variables**

*Component modularity*. Engine components "lose" degrees of freedom (or modularity) to the extent to which they have direct and indirect design interfaces with other components in the engine. We argue that there are two ways by which component *i* may lose modularity by interacting with component *j*. First, component *i* loses modularity by directly interacting with component *j*. The stronger the design interface of component *i* with component *j*, $m_{ij}$, the fewer degrees of freedom for modifying the design of this component and the more it will be affected by changes that might occur in component *j*. Second, component *i* may lose modularity if it interacts with another component *q* that also interacts with component *j*. That is, component *i* is additionally constrained by indirect design interfaces with component *j* through component *q*, as changes in *j* can affect *i* directly ($m_{ij} > 0$) and indirectly through its effects on component *q* ($m_{iq}m_{qj} > 0$). These two mechanisms are captured by the following expression measuring component *i*'s loss of modularity (*lm*) due to its direct and indirect interfaces with *j:*

$$(lm)_{ij} = \left[ m_{ij} + \sum_{q} m_{iq} m_{qj} \right]^2 \;\; ; i \neq j \neq q$$

where $m_{ij}$ corresponds to the standardized design interface between components *i* and *j* discussed before.

It is worth recalling that $m_{ij}$ captures the marginal strength of the design interface between components *i* and *j* with respect to the strongest design interface within the product. By squaring the previous expression, our measure assumes that modularity is lost exponentially as direct and indirect design interfaces become stronger, and that there is an additional loss caused by the joint occurrence of direct and indirect design interfaces.[7] The total loss of modularity for component *i* is simply the sum of the losses caused by each of its direct and indirect interfaces across all components *j* for which $m_{ij} > 0$, $\sum_j lm_{ij}$. Thus, component modularity diminishes with the number and with the strength of the direct and indirect design interfaces of that component. We reverse-coded the scores by multiplying each figure by negative 1 and dividing by 100 to facilitate the interpretation of the statistical analysis results. This is our measure of component modularity[8]. Figure 4 shows the ego network of the most and least modular components of the engine studied.

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[7] It is worth noting that our measure of component modularity is directly inspired by the measure of "constraint" proposed by Burt (1992:54–55) in the social networks literature, which we use in this paper to measure lack of structural holes in the team's communication network. Unlike Burt's measure of constraint, however, our measure of modularity uses a marginal transformation of the design interfaces $m_{ij}$, rather than the proportional measure he uses to capture the strength of social relationships. Indeed, using a proportional measure would have assumed that components (like social actors) have limited capacity to share interfaces with other components in the product, and that the strength of a given interface decreases as a function of the number of interfaces in which the specific components are involved. Such assumptions are not granted for physical systems. Finally, using a proportional measure would cause modularity to *increase* with the number and the strength of the design interfaces, which is contrary to the intuition behind the concept.

[8] We introduce a measure of component modularity based on the notion of constraint (Burt 1992) in order to test the effects of similar network structures in both product and organizational domains.

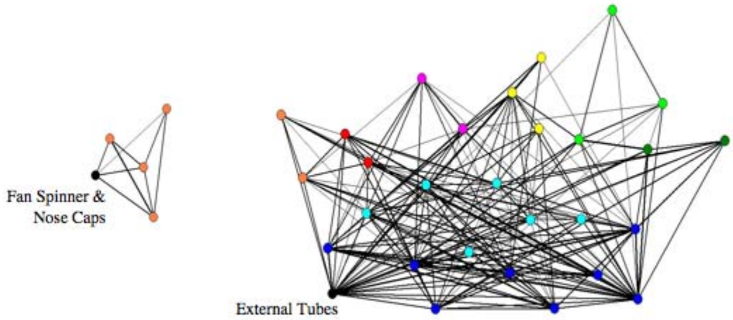


**Figure 4. Network structure for two components with the lowest and highest modularity**

*Structural holes.* Following Burt (1992), we measure team *i*'s lack of structural holes in the communication network as the sum of the constraint posed by each of the other teams *j* in *i*'s network. This constraint is in turn a function of the direct communication between *i* and *j* and of the extent to which *j* interacts with another team *q* also in *i*'s network (see Burt 1992: 50–71, for detailed discussion of this measure):

$$c_{ij} = \left[ p_{ij} + \sum_q p_{iq} p_{qj} \right]^2 \qquad ; i \neq j$$

where $p_{ij}$ captures the proportion of time and energy team *i* devotes to its communication with team *j* and $\sum_i p_{ij} = 1$. Note that this measure assumes that structural holes decrease as the team's communication is concentrated on a few other teams that interact strongly with one another. Hence, the lack of structural holes in a team's communication network is the sum of the constraint posed by each of its interactions with the other teams in the project: $C_i = \sum_{j \neq i} c_{ij}$

*Component redesign*. We define component redesign as the percentage of actual novel design content in a component, relative to the design of this component in the previous version of the product. As it is physically impossible to determine the exact amount of redesign in a component, we relied on percentage estimates by the design teams of the amount of redesign for their respective components in comparison to the prior existing engine. Specifically, we asked team informants to provide an estimate of the level of redesign required for "your parts or system for the PW4098, as a percentage of the prior existing engine design." This question provided a clear reference point to capture planned redesign due to new design content of the component itself as well as redesign to adapt the component to the new engine.

*Team size.* The effects of component modularity and redesign on a team's ability to attend to interdependences might be affected by the resources available to the team. A team's resources might also affect its ability to maintain an adequate communication network. Because managers are likely to allocate resources to teams taking into account the workload that results from the level of modularity of the component and the extent to which the team is expected to redesign that component for the specific generation of the product, the effects of modularity and redesign may be confounded with the effects of the resources available to the team. To control for this possibility, we include a four-point discrete variable accounting for the manpower resources allocated to teams. Although we were unable to collect precise data on team size—which was also variable throughout different stages of the process—we were able to obtain a qualitative assessment of team size based on the experience of one of the authors in the project, who is a design expert with substantial experience in similar engine programs and who also reviewed the design work for this particular project.

**Model estimation**

Two characteristics of our data impose specific constraints on model estimation. First, because our dependent variable is a proportion such as $0 \leq y \leq 1$, standard ordinary least squares (OLS) estimates may not be appropriate, for two reasons. First, the predicted values from an OLS regression can never be guaranteed to fall within the unit interval. Second, the coefficient of a linear model assumes that the effect of $x$ is constant across all levels of $y$, which again may not be accurate. A standard solution to this problem is to estimate a linear model for the log-odds ratio of the dependent variable. This approach, however, cannot be applied to observations where $y_i$ takes on values of 0 or 1, which forces the introduction of an adjustment before computing the log-odds ratio. A better alternative, proposed by Papke and Wooldridge (1996), is to use the following model:

$$E(y_i \mid x_i) = G(\beta x_i)$$

where $G(.)$ is the logit function. This approach does not require any adjustment of the data for extreme values of 0 and 1: The conditional expectations of $y$ given $x$ is estimated directly using non-linear least squares (see Papke and Wooldridge 1996 for details). To estimate this model, we relied on the procedure implemented in *Stata-SE 9,* estimating a generalized linear model (GLM) with a binomial distribution of the dependent variable, a logit function and robust standard errors.

A second characteristic of the data is that the components of the PW4098 engine were architected into eight systems, with their corresponding design teams organized in a similar way. Typically, interfaces within systems were significantly stronger than interfaces across systems, and the same occurred with communication ties between teams (Sosa et al. 2004). This suggests that observations within a given system may not be independent. To account for this condition, we estimate the model adjusting standard errors for intragroup correlation using the cluster procedure implemented in *Stata*.

## 4. Analysis and Results

Table 1 presents descriptive statistics of the variables in the analysis. As expected, team size is positively correlated with the team's ability to attend to technical interdependences. Team size is significantly correlated to component modularity ($r$ = -.385, $p < .01$). The simple correlation with redesign, however, is not significant. Yet, when the effect of modularity is held constant, redesign has the expected positive association with team size (4.33 $t$-value), with both variables explaining 20% of the variance in team size. This confirms the expectation that managers did consider both modularity and redesign when assigning resources to teams and provides legitimacy for our qualitative estimate of team resources. Team size is also negatively associated with lack of structural holes in the communication network ($r$ = -0.574, $p < .01$), suggesting that the ability to sustain a large and sparse communication network increased with the resources available to the team. Finally, modularity is positively associated with communication networks lacking structural holes ($r$ = .605, $p < .01$), suggesting that teams in charge of modular components were less likely to have large and sparse communication networks.

**Table 1. Descriptive statistics and correlations of variables**

| Variables | Min | Max | Mean | S.D. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|
| 1. Fraction of attended interdependences | 0.33 | 1.00 | 0.696 | 0.167 | | | | |
| 2. Team size | 1 | 4 | 2.444 | 0.925 | 0.274** | | | |
| 3. Component modularity # | -4.41 | -0.07 | -1.027 | 1.129 | -0.084 | -0.385** | | |
| 4. Component redesign | 0.00 | 1.00 | 0.487 | 0.333 | 0.168 | 0.142 | 0.229* | |
| 5. Team network constraint† | 0.12 | 0.48 | 0.249 | 0.091 | -0.386** | -0.574** | 0.605** | 0.097 |

* $p < .05$; ** $p < .01$

# Component modularity is computed using the network of 54 engine components.

† Team constraint is calculated on the communication network of the 60 design and integration teams using *UCINET* (Borgatti et al. 2002).

Table 2 presents GLM estimates of the effects of the independent variables on the team's ability to attend to technical interdependences. Models 1 to 4 report the main effects of the dependent variables, whereas models 5 and 6 report the effects of the interaction between team network constraint with component modularity and redesign respectively. Following standard practice, we centered the predictors on their mean to facilitate the interpretation of the interaction results and to mitigate the effects of multicollinearity between the main variable and the interaction terms. In order to assess the goodness of fit of our models we estimate the quasi-likelihood ratio (QRT) statistic suggested by Papke and Wooldridge (1996: 624-625), which has a limiting chi-square distribution.

Team size has a significant positive effect on the team's ability to attend to technical interdependences. Albeit weaker, this effect is still significant once both component modularity and redesign are held constant (Model 3). This result suggests that managers did consider the impact of component modularity and redesign on the team's workload, which is consistent with the fact that modularity and redesign account for 20 percent of the variance in team size.

Model 3 does not offer support for the predicted effects of component modularity and redesign on a team's attendance to technical interdependences. Once team resources are held constant, the modularity of the component and the extent to which the component was undergoing design changes did not seem to affect the team's attendance to its technical interdependences. A possible interpretation of this result is that the managers' ability to adjust team capacity to the varying workload resulting from the complexity of the component interfaces (modularity) and from the changes from previous generations (redesign) effectively countervailed the strain put on team resources by these two factors affecting the team workload. This interpretation, however, is not consistent with the results in Model 4, which includes the effect of the team's communication network structure. Once the effects of the team's communication network structure are held constant, component modularity has the expected positive effect on attendance to technical interdependences predicted by *H1*. Although the effect of component modularity is not strong ($p < .10$), it does suggest that managers might have not been totally able to assess *a priori* the effects of lack of modularity on team workload (Mihm et al. 2003, Clarkson et al. 2004). Model 4 also provides support for *H3*: the coefficient for team constraint is significant and negative, indicating that teams with a communication network rich in structural holes are more likely to attend to a larger fraction of their interdependences. It is also worth noting that Model 4 significantly improves the goodness of fit over Model 3, confirming the explanatory importance of communication network structure.

**Table 2. Effects on attendance to technical interdependence†**

| Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| Intercept | .251 | .318 | .334 | .786*** | .030 | .776*** |
| | (.278) | (.248) | (.295) | (.293) | (.551) | (.318) |
| Team size | .240** | .214** | .207* | .027 | .075 | .023 |
| | (.132) | (.111) | (.135) | (.108) | (.116) | (.119) |
| Component modularity | .019 | | -.012 | .132* | 1.070*** | .191** |
| | (.082) | | (.086) | (.099) | (.400) | (.089) |
| Component redesign | | .310 | .322 | .401 | .314 | .148 |
| | | (.320) | (.346) | (.413) | (.296) | (.347) |
| Team constraint | | | | -4.192** | -12.519*** | -4.494** |
| | | | | (2.339) | (3.349) | (1.835) |
| Component modularity x Team network constraint | | | | | 11.193*** (4.693) | |
| Team network constraint x Component redesign | | | | | | 6.942** (4.050) |
| QLR[a,b] | 0.031 | 0.898 | 0.899 | 7.744*** | 19.907*** | 11.046*** |
| *N* | 54 | 54 | 54 | 54 | 54 | 54 |

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$ *(one-tailed tests)*

† Robust standard errors adjusted for eight clusters in the system are shown in parentheses.

a: Quasi-likelihood ratio (QLR) ≡2(Unrestricted Deviance – Restricted Deviance) / (Unrestricted Pearson/Unrestricted residual df)

b: The baseline model against which QLR is estimated for Models 1, 2 and 3 includes team size only. QLR for Model 4 is estimated against model 3, and QLR for models 5 and 6 is estimated against Model 4.

The fact that the positive effect of high modularity (i.e., a more predictable workload) becomes apparent only after controlling for the effect of communication network structure merits attention. Team constraint (our measure of communication network structure) is correlated with modularity ($r$ = .605, $p < .01$), suggesting that teams in charge of modular components are more likely to have relatively smaller and more closely knit communication networks. Because team constraint has a significant *negative* effect on the attendance to interdependences and it is positively correlated with modularity, the effect of component modularity becomes apparent only once team constraint is controlled for in Model 4.

Component redesign remains insignificant after holding the effect of communication network structure constant. While this may simply imply that managers were more able to account for the expected effects of component redesign at the time of allocating resources to the team than they were when considering the additional complexity caused by the lack of component modularity, the lack of a clear association between redesign and attendance to interdependences could also result from two conflicting mechanisms associated with component redesign. On one hand, high redesign focuses the team's attention on inherent design issues associated with the component itself, and away from the interfaces with other components. On the other hand, a team that is undertaking a significant component redesign is more likely to attract the attention of other teams whose work may be directly or indirectly affected by such redesign. While the first mechanism is likely to reduce the focal team's attention to technical interdependences, the second mechanism is likely to increase that attention, as the signals the focal team gets from other teams raise its awareness of the potential effects the redesigned component might have on other components in the product. If these two conflicting mechanisms operate at once, the net effect of component redesign on the team's attendance to technical interdependences might not be apparent. Additional evidence from the interaction between redesign and team network structure suggest that this is more likely to be the case for components with high redesign.

Models 5 and 6 introduce the interactions between team network constraint and component modularity and redesign, respectively. In line with *H4,* Model 5 shows a positive and significant interaction effect of component modularity and team constraint. The magnitude of the main effect and interaction coefficients suggest that modularity mitigates the positive effect of network structure rich in structural holes, but it does not reverse such an effect. That is, teams exhibiting a network rich in structural holes are more likely to attend their technical interdependences when designing more integral (i.e., less modular) components. Yet the mitigation effect of component modularity is not large enough to make closely-knit communication network structures more attractive when designing highly modular components. (Note that even with a maximum centered component modularity of 0.96 the total effect of team constraint on our dependent variable is still negative.) As a result, the less modular the component, the larger the benefits of having a communication network structure rich in structural holes (in line with *H4*).

Supporting *H5*, Model 6 shows a positive and significant interaction effect of component redesign and team constraint. This result suggests that teams facing low component redesign are more likely to benefit from large and sparse communication networks, as their ability to attend to technical interdependences is not limited by capacity constraints resulting from component redesign; rather, it stems from lack of adequate information about how events associated with other components might affect their own work. The result also suggests that teams whose components are undergoing significant redesign are less likely to benefit from a communication network rich in structural holes, although they still do to a certain extent. Indeed, the net effect of team constraint on our dependent variable remains negative for all levels of component redesign, including the maximum observed score for the mean-centered variable (that is, 0.51).

The results in Model 6 are also consistent with our conjecture about the effects of high component redesign on a team's ability to attend to interdependences. Teams engaged in substantial component redesign need to use their resources to resolve the uncertainties of the component design itself and to attend to the novel interfaces with other components simultaneously. The factor that may prevent the team from focusing its attention on the interfaces is not lack of information about developments in other teams, but rather the immediacy of the work on its own component, which is likely to turn the attention away from the interfaces. In such a situation, the benefits of a large and sparse network that provides non-redundant information on events that occur elsewhere in the development effort are less apparent, whereas the costs of such a network—materialized in weaker and potentially conflicting signals about the effect of the redesign on other teams—should be more salient. In this sense, the coefficient for the interaction effect between redesign and communication network structure is consistent with our argument on the two conflicting mechanisms through which high component redesign may affect a focal team's ability to attend to technical interdependences: an endogenous mechanism that drives the team's attention to the component, and an exogenous mechanism by which the signals from teams affected by redesign can drive the attention of the focal team to the interfaces with other components. Teams with low levels of component redesign, on the other hand, need to focus on the interfaces with other components, because such interfaces are the primary sources of design uncertainty. The more those teams maintain large and sparse communication networks, the more likely it is that the team will access information on those interfaces, and the higher their capability to attend to more technical interdependences.

## 5. Discussion

The main question we address in this paper is: What drives the capability of teams to attend to their technical interdependences? Is it the product structure, the organizational structure or both? This is particularly relevant in complex product development, where one main challenge is coordinating and integrating the effort of design teams. Therefore, understanding the factors that determine the capability of teams to attend to interdependences is critical for managers of complex development projects.

We found that a sparse team communication network—that is, a network rich in structural holes—has a significant impact on the capability of teams to attend to technical interdependences. However, such an effect is mitigated by the level of modularity and redesign of the components. This is important to realize because complex products typically involve a web of components that exhibit various degrees of connectivity among themselves and various levels of novelty, as some components are entirely new whereas others are completely carried over from previous product generations. Hence, it is important for managers to realize that in order to increase the capacity of design teams to attend to their relevant technical interdependences managers need to pay close attention to the structure of their technical communication networks and the factors that moderate their benefits.

We found that teams surrounded by a sparse network rich in structural holes are better positioned to focus on the relevant interfaces and therefore exhibit higher levels of attendance to interfaces.

Interestingly, we found that the positive effects of structural holes are particularly beneficial for teams designing either highly integral components or highly reused components. That is, for highly integral components, teams surrounded by structural holes benefit from investing in a large and sparse network, which allows them to attend to more interdependences than teams using a more cohesive communication network. Similarly, for components that exhibit a low percentage of redesign, teams whose communication networks span many structural holes are more likely to find out which interfaces to address, which results in a superior ability to address as many relevant interfaces as needed. These results have an important managerial implication. Maintaining a large and sparse communication network is expensive and may require special communication mechanisms. Such a network may also jeopardize cooperation with adjacent teams, which can be important when the focal team is engaged in substantial component redesign. Hence, by examining the degree of novelty and modularity of the components managers can anticipate which teams may require special attention and investment to maintain a large and sparse communication network.

Additional fieldwork evidence from the project studied validates our quantitative results and illustrates the differences between cohesive and sparse communication mechanisms. We observed that many teams with sparse communication networks (such as the air system team or the controls sensor team) attended a significant amount of design interfaces distributed physically and functionally throughout the engine. Most of these teams used several mechanisms to encourage effective interface handling, such as regular model updates and formal information releases. All these structured and codified communication mechanisms allowed teams with many structural holes to attend to larger fractions of interdependences, even with teams that were organizationally distant from them. Note that the nature of the interfaces with which many low-constraint teams dealt were usually connective rather than discrete (e.g., transfer of air, oil, signals or loads from one component to another; providing communication controls, heating or cooling). As a result, different communication mechanisms, such as interface diagrams and structural and thermal model summaries, were put in place so that multiple participants from multiple teams have ready access to check, review and update their components. Teams designing less-modular components had significantly more crosscomponent and cross-system interfaces to attend to, but had less engineering work to do per component than the teams designing more modular but more engineering-intensive components, leaving them less time to manage their interfaces outside of their systems. Given this, each type of team had to develop tools that made their work more efficient within the time allotted. Some teams developed communication-enabling tools that allowed them to span structural holes, while other teams developed more automated engineering analytical tools that could be used within a cohesive network with other teams.

For teams exhibiting more cohesive communication networks (such as the fan hub team or the high-pressure compressor [HPC] fixed stators team) interfaces were managed the “old way”—that is, with less communication but sufficient and efficient enough to provide them the information they needed when they needed it. This was optimal for them because their lead times were limited by engineering analysis and by part definition leading to long production cycles (e.g., major castings and custom forgings of super-alloys). For these teams, component modularity helped them attend to a larger fraction of interdependences. For example, although both the fan hubs and the HPC fixed stators were expecting to have similar levels of redesign around 70%, the connectivity of the latter was significantly larger than the former, resulting in higher workload and significantly less attention to many design interfaces. This observation is consistent with the results presented in Model 5 (Table 2.)

Finally, we also observed that communication mechanisms used by teams with sparse networks served them better when they had low levels of component redesign (consistent with the results shown in Model 6 of Table 2), because those mechanisms allowed them to review most of their design criteria and interfaces to ensure that they stayed within limits and facilitate and communicate the minor changes to associated teams with which they collaborated. On the other hand, teams that exhibited more cohesive communication networks (i.e., high team constraint) and low component redesign—such as the high-pressure turbine blades, which had just 25% redesign—communicated typically about discrete interfaces with few other adjacent teams, leaving some more distant interfaces unattended: They expected these interfaces to remain largely unchanged and accordingly behaved reactively to them.

We checked the robustness of our results against alternative definitions of our dependent variable. First, we defined an alternative measure of fraction of attendance to interdependence, which ignores unidentified team interdependences (in both the numerator and the denominator of our dependent variable). The results are slightly more significant than the ones shown in Table 2. We also considered unidentified interdependences as the result of spurious or redundant interactions by removing them from the numerator of our dependent variable, but including them in the denominator as these interactions consume team resources. The results with this alternative definition are even more significant than the ones reported in this paper. Finally, although the generality of our findings must be treated with care given the nature of our data, we believe similar results would be found in other complex design projects where the product structure is formed by a mix of new and redesigned components and whose development organization maps directly to the architecture of the product. Nonetheless, external validation of our findings is needed, which opens interesting opportunities for future research in this area.

## 6. Conclusions and Future Work

As Simon (1981) suggested, complex systems are difficult to understand because the behavior of the whole depends in non-trivial ways on how its elements interact. A network approach focused on capturing the elements of the system and their linkages can be very fruitful in understanding how complex innovation systems work. We have applied a network approach to study the interactions across the network structure of a complex product and the complex organization that designed it. This has important implications for both operations management and organizational theory. For operations management, we show how network attributes of product components such as modularity can be measured so that the impact of components' connectivity can be studied. In addition, we also learn that although component modularity can help teams attend to a larger fraction of interdependence, the benefits of modularity reach a limit that can be surpassed only by examining the organizational structure. For organizational theory, we show that it is important to understand not only which network structure provides more benefits to design teams but also what determinants of design tasks can moderate the impact of social networks. We found that the benefits of sparse networks are contingent on important attributes of the product components, such as their modularity and their level of redesign.

While our paper is successful in addressing the questions posed in our introduction, it also raises a number of other interesting questions that can stimulate future research on the topic. Are teams surrounded by structural holes better positioned to mitigate design oscillations? Are certain project tasks more likely to generate teams surrounded by structural holes? Further research is also required to understand the dynamics of these complex systems. How do product structures evolve over time? How do organizations cope with such evolution? How does closing a structural hole affect organizational performance? By fruitfully combining insights from operations management and network analysis, we believe that we have delineated a path that can help researchers address these important questions.

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