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The Impact of Information Technology on Coordination: Evidence from the B-2 "Stealth" Bomber

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The expected impact of information technology on organization has been described theoretically. It has also been examined in large sample quantitative studies. In this paper, the impact of information technology on organization is described in rich detail through the use of a case study. The insights generated from this case study, in many cases, outstrip the insights that have been generated by earlier work.

Jay B. Barney

Abstract

This paper explores the economic processes through which information technology can facilitate coordination within and between firms. The paper presents and analyzes a case study of the B-2 "Stealth" bomber, an aircraft that was designed by four firms almost entirely by computer. The key information systems used in the project were (1) a common-access database to manage part designs and (2) an advanced system to perform structural analysis. These systems played a crucial role in enabling the four firms to coordinate their design and development activities precisely enough to meet the demanding engineering requirements imposed by the aircraft's unique mission. The paper analyses the case study using transaction cost, agency, and information processing theories.

The analysis leads to several conclusions about the mechanisms through which the variables emphasized in these theories operated to improve coordination. First, the information systems aided coordination directly by making information processing less costly. Second, this enhanced information processing made the governance of the project more efficient. In particular, by establishing a "technical grammar" for communication, the systems helped to create social conventions around which firms could coordinate their activities, thus limiting the need for a hierarchical authority to promote coordination. This technical grammar also reduced governance costs by reducing asset-specificity, thereby reducing risks associated with contractual holdup. These interactions between communication and governance effects have not been elucidated in the IT/coordination literature. They are important in part because they help explain why the vertically disintegrated organization of the project proved viable. Finally, the systems facilitated decentralized decision-making by reducing agency (measurement) costs. This combination of effects may generalize to other settings in which information technology is used to promote coordination, especially in "virtual" or "disaggregated" corporations.

(*Information Technology*; *Coordination*; *Governance*)

The industrial future, we are told, belongs not to large bureaucratic organizations, but to networks of small affiliated companies that exchange with each other using advanced information systems. These networks have been dubbed "virtual corporations." (Davidow and Malone 1992, Byrne 1993) Malone et al. (1987), for example, have argued that information systems reduce the costs of coordination between buyers and suppliers, leading to a greater reliance on markets to organize economic activity at the expense of hierarchies. In support of this claim, Brynjolffson et al. (1994) found that increases in information technology (IT) investments by U.S. firms have been associated with a decline in firm size.

Scholars have also argued that advanced IT is leading to more decentralization of decision-making within firms. Zenger and Hesterly (1997) hold that firms are using IT to "disaggregate" their activities to facilitate decentralization. Johnston and Lawrence (1988), Lawler (1988), and others argue that by reducing unit costs of processing

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information, IT is substituting for many functions of an organization's bureaucracy. This, they claim, is helping to cause the often-discussed flattening and decentralization of organization structures within U.S. firms.

In this paper, I investigate the economic mechanisms through which advanced information technology (IT) can enhance coordination within and between firms. The aim is to shed light on the factors that may underlie the changes in economic organization that scholars are observing. In this way, the study can help us to assess the claims made in the popular and academic literatures about the affects of IT on economic organization, and to sharpen our predictions about future such impacts. The investigation is carried out by examining the role played by IT in an early example of a virtual corporation: the network of firms that, starting in the early 1980s, designed and developed the B-2 "Stealth" bomber, a highly advanced military aircraft. The B-2 is of particular interest because it was the first major U.S. aerospace program to rely on a single engineering database to coordinate the activities of the major subcontractors on a large-scale design and development project. The database eventually contained nearly all the information necessary to build the highly complex and innovative aircraft—information that was directly used both in advanced structural analyses and to create machine tools and control machines to manufacture all major aircraft sections. The Stealth bomber project thereby achieved a high level of "electronic integration" between the contractual partners. As such, it offers a unique natural laboratory for studying the economic mechanisms through which IT can make virtual and disaggregated corporations into viable organizational forms. Information systems are of course far from homogeneous. The assumption of this study, however, is that by examining the functional characteristics of one system in some detail, insights can be gained about the relationship between specific features of information systems and the organization structures or modes of governance the systems tend to encourage.

Understanding the underlying processes by which IT enhances coordination is an important step toward understanding how IT can improve the efficiency with which large-scale projects are carried out. This is especially important in a military context. Since modern warfare is increasingly conducted or deterred with advanced technology, solving coordination problems in high-tech military projects is an increasingly important capability for military institutions and their associated firms to possess. By influencing these coordination capabilities, IT will increasingly affect the distribution of military power among nations, and its impact on international political and economic outcomes will grow. Studying how IT can improve coordination is also a first step toward understanding how it can improve organizational design, as well as how it can change organizational boundaries. For example, whether integrated IT encourages increased use of market contracting, hierarchy, or intermediate forms such as virtual organizations and relational contracting, is largely a function of the precise ways in which it affects coordination.

In this paper, I draw upon economic theories of organizations to interpret and generalize from the Stealth bomber experience.[1] These theories are increasingly finding application to the question of how IT can improve the coordination of activities within and between firms. The applications usually seek to combine insights from the economics of organizations with insights from information processing approaches to organization. For example, research in organizational information processing by authors such as Marschak and Radner (1972), Galbraith (1973, 1977), and Burton and Obel (1984) is applied to model IT as serving to improve information processing between organization members while economizing on scarce information processing capacity. Since IT reduces the costs of processing information (i.e., the costs of sending and receiving messages between actors) it can make some organizational structures more efficient than others.

Information processing approaches focus on the ways in which IT increases the quantity of information—the number of messages—transmitted and received per unit of time. In particular, IT is seen as providing a means of increasing this quantity. Such approaches, however, generally abstract from the problem of motivating actors to process information in an accurate and timely way. Contributions applying organizational economics, including Malone et al. (1987), Gurbaxani and Whang (1991), Clemons et al. (1993), Ciborra (1993), and Picot et al. (1996), emphasize that IT may play a role in providing incentives for actors to ensure the quality of messages they send, and to make efforts to receive and interpret messages accurately. According to this view, IT may help to create and support a set of governance arrangements that enable exchanges of information and other goods to be carried out without large transaction costs. These transaction costs arise from incentive misalignments and potential opportunism by agents—considerations that are absent from information processing approaches. For example, inspired by the agency theory literature (e.g., Alchian and Demsetz 1972, Jensen and Meckling 1976), IT scholars have been concerned with how IT can help create incentives for organization members to mitigate problems of moral hazard. Drawing on transaction cost economics, they have also discussed how IT can reduce the costs associated with potential opportunism in buyer-supplier exchanges, paying particular attention to IT's role in reducing various forms of asset-specificity. This is the key theoretical variable emphasized by Williamson (1975, 1985) and Klein et al. (1978) as determining organizational boundaries. Applications of transaction cost economics to IT are thus particularly useful for understanding how IT, by improving coordination between autonomous organizations, can cause changes in those boundaries.

In order to understand the full range of IT's functions, organizational impact and potential power, scholars have found it necessary to apply information processing and transaction cost approaches jointly. This is in part because IT is often used to manage complex, information-intensive transactions—situations in which problems of information processing and problems of governance arise simultaneously. This suggests the need to understand the effects of IT on both the *means* and *incentives* for communication within the between organizations, and to theorize about how the interaction of these effects can improve coordination. This exercise is important in developing the theoretical basis for predictions about how IT influences choices of organizational structure and governance mode. This paper attempts such an exercise by analyzing a set of empirical examples of the application of IT in organization settings—examples which are detailed enough to assist in the development of an integrated theory of the underlying economic mechanisms by which IT affects coordination.

The theoretical interpretations of the main case material suggest a number of insights about the role of IT in the B-2 project. The B-2 information systems can be seen as serving to establish a highly standardized technical "grammar" with which communication about complex component and subsystem designs could occur between engineers and managers from different companies. The establishment of this grammar, or communication channel, allowed a "technical dialog" (Monteverde 1995) to occur, which served to reduce the total amount of information that needed to be exchanged between the firms for the project to be completed successfully. In this sense, the costs of information processing were reduced relative to what they would have been without the information system. This in turn enabled designers to make design decisions based on accurate expectations about each other's design plans, allowing convergence to a relatively efficient outcome. The technical grammar can thus be interpreted as a set of social conventions around which engineers and managers from different firms could coordinate their activities without extensive communication between them (Schelling 1978).

The establishment of a standard grammar for communication also served to improve the governance of the project. First, the costs of governing the contractual relationships between the various major subcontractors were reduced because the costs and risks of contractual holdups by the subcontractors were decreased. The technical grammar served to limit the amount of specific human capital investment required for project—investment that was vulnerable to expropriation by contractual partners. Thus, the superior communication achieved by the B-2 information systems improved coordination between the independent firms by reducing the costs of using market-governed contractual relationships between them. Second, the social convention aspect of the technical grammar limited the need for a single hierarchical authority to promote coordination on the project. This restricted role for authority enabled the project to avoid costly influence activities that often plague hierarchical organizations (Milgrom and Roberts 1988, 1991). Finally, particular features of the systems allowed continuous measurement of the performances of individuals involved in development and manufacturing activities, thus reducing the costs of monitoring the performance of contractual partners. Measurement costs are agency costs that arise in transactions between independent organizations (Barzel 1982). Thus, the special features of the B-2 information systems improved coordination by simultaneously limiting requisite information processing and reducing several specific types of governance costs. Moreover, this governance cost reduction was partly caused by the improved information processing that the technical grammar afforded.

This interpretation of the effects of the B-2 information systems provides a way of understanding how the systems made the virtual organization a viable organization form for the Stealth bomber project. The increased quantity of information processed improved coordination directly, as well as indirectly through a reduction in governance costs. Governance costs also operated directly to improve coordination. The combination of direct and interaction effects observed in this project may generalize to other settings and other types of information systems—especially systems facilitating group work—and suggest plausible mechanisms by which IT can substitute for hierarchy.

The case study material of primary concern in the paper show how a particular information system aided coordination on a complex project, once that system was adopted by the parties. However, case material about how the information system was adopted in the first place, though it involves a secondary issue for the purposes of this paper, is also presented and interpreted. This supplemental case material provides useful context for the main material, and bears on the issues of interfirm standards adoption and knowledge-based determinants of firm boundaries.

After a brief discussion of the research methodology, the case material is presented in four parts. The first part consists of general background on the Stealth bomber. The second part presents the supplemental case material on the systems adoption process, along with interpretations. The third and fourth parts present the main case material, and interpretations of it, concerning the "product definition system" and the "structural analysis system" used to build the aircraft. Conclusions follow.

Methodology

Exploring and discriminating among the theoretical mechanisms discussed above requires detailed data concerning particular transactions. This is because the transaction is the unit of analysis in much of organizational economics. The data below were gathered through interviews with engineers and managers who were involved in designing the B-2, with industry IT experts, and from some recently declassified Northrop/Grumman documents. Key informants included a former B-2 Project Manager, who had responsibility for all aspects of the project, and two former chief engineers for the B-2 project, each of whom served in other important B-2 positions over the development period. Design, manufacturing, and systems engineers who developed and/or used the B-2 systems were also interviewed.

The interviews were loosely structured. Respondents were asked, for example, to describe the functioning of the B-2 information systems, provide their views of the systems' critical attributes, and highlight the most important ways that the system affected the manner in which design and engineering work was carried out. In most instances, respondents' relatively objective descriptions were enough to shed light on the theoretical mechanisms of concern. More subjective questions centered on conflicts that arose during the project, which is an important issue for the analysis of governance. Interviewees from the various firms provided very similar accounts of the conflicts that were discussed. All of the case study materials are based on primary sources, with a few exceptions that are identifiable by immediate references to secondary sources.

Design and Development of the B-2 Stealth Bomber

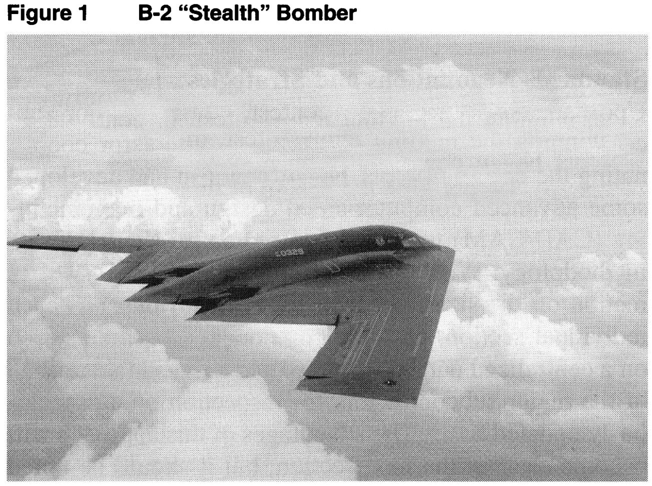
Background

The Stealth bomber is a military aircraft designed and built for the U.S. Air Force in what it has called "the most successful modern aircraft development program ever" from the point of view of efficient organization (Sweetman 1989). Managers of the firms that designed the aircraft also describe the development process as remarkably smooth, especially in view of the complexity involved. The project proceeded under very tight secrecy, operating under a classified development contract. Much of the program remains classified as of this writing. The B-2 has been described as "America's biggest military secret since the Atom Bomb" (Scott 1991).

The Stealth bomber was designed to be "low-observable"; it is very difficult to detect by radar or other means. "Stealth" is its fundamental innovation and raison d'etre, and is accomplished by the plane's overall shape, complex surface, use of advanced radar-absorbent material, and use of engines free of thermal and acoustic "signatures." The design considerations are explained as follows. Radar operates by transmitting a radio-frequency signal through an antenna that focuses it into a conical beam. If a reflective object blocks part of the beam that part is scattered. Some reflected energy is picked up by the antenna, which acts as a receiver between signals. The degree of reflectivity of the object will significantly affect its detectability. Conventional airplanes are highly detectable because elements of their shape produce strong radar reflections, especially from angles between the wings and fuselage, exposed engines, riveting on exterior panels, etc. The Stealth bomber reduces reflectivity to a large extent by using a "flying-wing" design (see Figure 1), with engines concealed, and by using very complex shaping laws over the surface of the aircraft. This shaping, still largely secret and not well understood by outsiders, is based on curves that constantly change radius to reflect radar away from the emitting antenna.

Developing such shaping or "sculpturing" was a major

Figure 1 B-2 "Stealth" Bomber



U.S. Air Force photo by Master Sgt. Rose Reynolds

innovation in aircraft design (Sweetman 1989). A crucial characteristic of this sculptured design was that it required that the various sections of the airplane to fit together extremely precisely, so as to ensure that the lines defining the sculpturing would "line up" consistently over the entire surface. Any "dimples," "edges" or "seams" on the surface would increase reflectivity, compromising low-observability. The engineering tolerances required were on the order of 1/10,000 of an inch, much greater that on conventional aircraft. In addition, all leading edges of the aircraft were covered with a special radar-absorbing material, developed as a proprietary technology by Northrop.

The Stealth bomber was designed during 1980–1986 by four large firms: Northrop (now Northrop/Grumman), Boeing, Vaught (then a division of LTV), and General Electric (GE). Hundreds of other firms supplied parts that were produced to specification. These firms held very little design responsibility. Northrop was the prime contractor on the project, with the other three firms acting as major subcontractors. Together the companies won the government-held bidding contest to design, develop and build the B-2. The primary development contract was structured differently than many such contracts. Generally, the Department of Defense funds development of new weapons systems, and firms spend their own funds in an effort to win the bidding contest. Winning firms are also granted a cost-plus production contract guaranteeing a certain rate of return on investment. In the case of the B-2, however, the development contract itself was a "cost-plus-incentive-fee" contract. That is, government payments were made on a cost-plus basis, but incentives to limit costs were also built into the contract. Thus, Northrop would receive an 8% rate of return if development work did not exceed their original estimate of work required. The rate, however, declined steeply with the difference between actual and estimated development costs, ending at zero.

Standards Negotiations and Strategies

Upon winning the bidding contest, the four major subcontractors began negotiations on a system for coordinating the design of the aircraft. Northrop had developed some advanced computer-aided design and manufacturing (CAD/CAM) tools and favored an all-digital design methodology. With this approach, comprehensive information on the sizes, shapes and other attributes of each individual section, part and component would be stored on a centralized database, and would be available to each of the major subcontractors for inspection on a continuously updated basis. The advantages of this approach will become clear in the next section, but it should be noted that Boeing and Vaught were initially less enthusiastic about all-digital design. As the former head Boeing engineer on the project explained,

> At this point in time we were developing our own system, CATIA, which we would eventually implement on the 777. We had already trained some of our people on that system, and we wanted to develop it. We knew we wouldn't be using CATIA if we had to be compatible with this huge, monolithic database.

According to the former B-2 project manager, Boeing and Vaught extended negotiations until they were threatened by Northrop with a "contract directive": an order to supply by the prime contractor which, if made after "good faith" negotiations, is court-enforceable. It was also suggested that the Air Force agreed to absorb a portion of the training costs Boeing and Vaught faced in an adjustment to the primary contract. Agreement on all-digital design was reached soon thereafter.

The next step was to agree on the particular form of the information system to be used. This involved negotiating a set of standards for the definition and transmission of data, the analysis of designs, and a format for a common database to store design data. At the time, Boeing, Vaught, and Northrop each were operating different, incompatible CAD/CAM systems. The group agreed to use a single set of tools for designing the surface of the aircraft: CAD/CAM programs created by Northrop for three-dimensional (3-D) modeling (NCAD and NCAL), and CADAM™, a commercially available system for traditional orthographic drawings. These drawings were necessary for parts to be manufactured by smaller suppliers that did not possess 3-D CAD systems. The tools included a standard for transmitting data and storing it in the common database, which was structured hierarchically. The group also agreed to use NASTRAN, a design analysis system developed by NASA.

Negotiations on the form of the system proceeded more quickly than the negotiations on all-digital design. Managers give several reasons for this. First, the Northrop design and analysis tools were clearly superior in functionality to CATIA (which was still under development) and to Vaught's (incompatible) proprietary system. Second, no commercial system contained a data transmission standard for defining and transmitting three-dimensional models between incompatible CAD systems. After some experimentation, it had been found that developing 3-D solid models was necessary to achieve the extreme accuracy and very high tolerance requirements in surface fits. Contemporary translators, such as IGES (Initial Graphics Exchange Standard), calculated to too few decimal places to allow transmission of data-intensive 3-D solid models, and were limited to 2-D and wire-frame models.

Agreement was achieved, therefore, on two levels. Each firm committed to using an all-digital design methodology, and then to the specific one based on Northrop tools. The former B-2 project manager mentioned an additional factor that facilitated negotiation on both levels. He claimed that aerospace companies are often reluctant to stall negotiations because they are concerned about their reputations. As he put it, "you don't want to be left off the next bid list." The number of major military aircraft projects is very small over any period, and only a handful of airframe firms can effectively compete to become prime contractors. At the time, the list was limited to Lockheed, Martin Marietta, McDonnell-Douglas, Grumman, Northrop, and Rockwell (and has since shrunk as a result of mergers).

Following negotiations within the group, each company assumed design responsibility for a different section of the aircraft (see Figure 2). Apparently, the choice of an all-digital design method did not affect the division of work among the various major subcontractors. The former project manager put it this way:

> [all-digital design] . . . didn't influence the "breaks" between the parts and the assignments of responsibilities. Each company had reasons for wanting a piece of the airplane. Boeing, being the largest commercial airplane builder in the world, wanted to learn how to build large composite skin panels for the wings on airplanes. At all costs they wanted to protect this work share, because they wanted to re-apply it to the 767, the 777, the '7X7'. Vaught . . . was building advanced control surfaces and exhaust structures for Boeing and McDonnell-Douglas and so on. So they wanted everything around the engine—because they could re-apply the technology to their other subcontracts. We [Northrop] were a systems integrator, and we were the ones who invented the "stealth" approach on this airplane. So the radar-absorbing rim material is something we wanted to protect. And because we were a systems integrator, we said we'll take the black boxes, electronic and hydraulic control systems, etc. So it was each company's unique strategy in terms of what they could walk out of this program with and reapply to future activities—that's what drove the breakdown of the airplane.

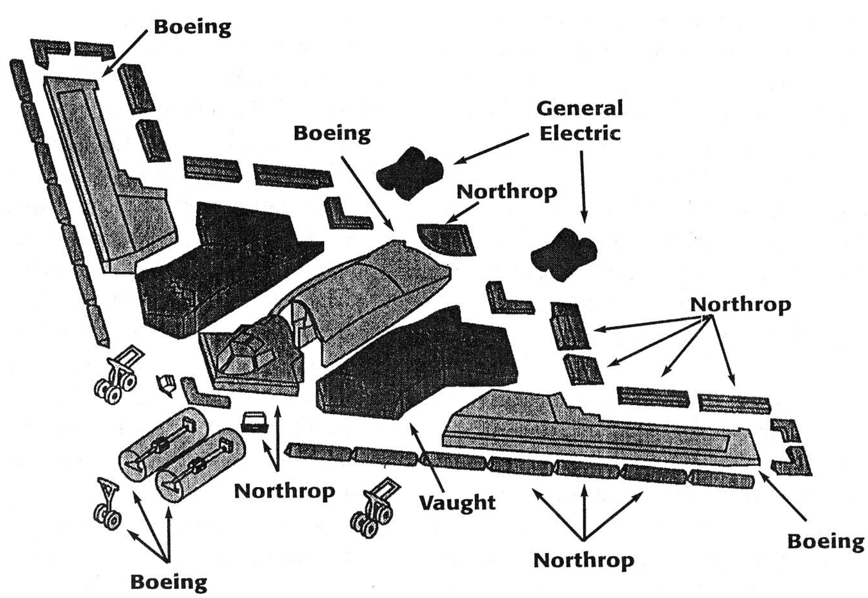
Did Northrop consider negotiating to build more of the airplane itself?

> The project was just too large. We wouldn't have been able to hire enough engineers. As it was we ended up hiring over 4,000. The program would have taken a huge [cost] hit if we had to pull people in from around the country, what with the California real estate market the way is was then.

Economizing on location costs appears to have been quite important. Scott (1991) estimates that over 8 million square feet of industrial space was used around the U.S. for B-2 development.

Another reason given for the subcontracting arrangement was that some companies had relatively unique capabilities. For example, only two companies in the U.S. (GE and Pratt & Whitney, a division of United Technologies) possessed the expertise to design the engines, and innovative, in-wing designs were required to meet the low-observability criterion. Another factor that may have been important (although it was not specifically mentioned by interviewees) was that extensive subcontracting

Figure 2 The Stealth Bomber



can serve to spread a project's work over several Congressional districts, which can improve its prospects for Congressional approval.

Interpretation

This section presents some theoretical interpretations of the supplemental case material concerning the systems adoption process. To implement advanced information systems, buyers and suppliers must agree on a set of compatibility standards for the definition and transmission of data. Without such standards, data will not be usable by its receivers. Information systems standards are found at a number of levels, including hardware, operating systems, and software applications. Transaction cost theory makes some predictions at this "systems standards" level of analysis. For example, opportunism may be an important barrier to adoption of common standards in these areas. Parties, be they firms or divisions, often have large sunk investments in hardware, software, and training that are incompatible with some standards, and may bargain and hold up negotiations on common standards to force adoption of their preferred standard. Or, because of strong uncertainty about how computer technology will evolve, parties may simply disagree on which standard is the more efficient one (Nelson and Winter 1982, Argyres 1995). From a transaction cost perspective, then, hierarchical organization would be preferred over contracting between (semi-) autonomous parties when a significant amount of coordination is required to design a highly interrelated system (Teece 1984, 1988).

If virtual corporations are understood as groupings of firms exchanging with each other using market contracts and shared information systems, transaction cost theory might recommend pessimism about their viability over time. This is because adopting such systems requires significant agreement on technical standards that are changing frequently as IT advances. Transaction cost theory might predict that such agreement would be difficult to engineer without more elaborate governance mechanisms. For example, in their study of Italian metal working firms, Cainarca et al. (1993) found that as technical standards for computer-based production technologies began to diffuse among these firms, more hierarchical control was exerted over transactions, mostly at the expense of long-term "partnership" arrangements with suppliers.

In the B-2 case, the relevant parties had to agree on technical standards at the level of the system as a whole (all-digital or not), and at the level of software applications, in order for the systems to aid in design and engineering coordination. While the parties to the B-2 project did manage to agree, there were several unusual circumstances that facilitated agreement—conditions that are quite consistent with insights from organizational economics. First, alternative database formats and applications existed, but had not reached the stage of development where they could compete with the Northrop systems. In game-theoretic terms, the Northrop system was an obvious "focal point." Moreover, firms had not yet made large specific investments in incompatible systems, so incentives to haggle were reduced. Boeing had begun to develop CATIA, but its commitment to it was still relatively modest. Also, the very small number of players in the industry allowed reputation effects to operate at some level, as illustrated by the reference to being "left off the next bid list" made by a Northrop manager. Finally, the Air Force's apparent willingness to help fund training reduced these incentives still further. The B-2 experience, then, would suggest some caution in assuming that information systems standards will diffuse quickly, and in a spontaneous way, across firms. Some type of hierarchical mechanism may be needed in the early stages of systems development and adoption in order to overcome inherent transaction cost and bargaining problems. This might imply centralization in cases of systems adoption internal to the firm, and at least some form of quasi-vertical integration (Monteverde and Teece 1982) in cases of adoption of buyer-supplier systems. A strong reputation mechanism could perhaps suffice, but the kinds of conflicts that arise over advanced technology are often complex enough that third parties cannot easily ascertain who was the more opportunistic party in a given conflict. Without this kind of external verifiability, reputation effects will be weak.

A second point to notice is that the organization of the B-2 project was chosen independently of the information systems, and before negotiations on systems characteristics began. The composition of the group of firms, and the division of work between them, was apparently driven by the bargaining positions the companies took, which were guided by their individual strategies of capability building and knowledge replication.[2] Because the choice of information system did not appear to affect the division of work, one can analyze the direct effects of the systems choice on governance without having to account for the indirect effects though the choice of project organization. That is, one does not have to analyze how systems choice affected the division of work, which in turn affected governance. The fact that this indirect linkage did not occur simplifies analysis of the case material.

Another implication of this is that the governance problem is a bit different than the one typically analyzed in transaction cost theory. In that theory, the characteristics of transactions are given exogeneously, and governance structures are chosen to match those characteristics. In the B-2 case, however, the governance structure was apparently chosen for reasons other than transaction costs: namely, knowledge development and diseconomies of locational scale.[3] Therefore, the relevant governance problem in the B-2 case was to adjust the transaction characteristics so as to limit the hazards of contracting, taking basic features of the governance structure as given.

The B-2 Product Definition System

This section presents the first part of the main case material. The B-2 design process was based on what was called a "product definition system." Engineers working for the major subcontractors created 3-D models of components and sections using NCAD and NCAL, which were then stored, along with orthographic drawings in CADAM™, on a single master database. The drawings were stored on a detailed part, subassembly, and assembly basis. The centralized database was established at Northrop's Pico Rivera, California facility and was made accessible to all major subcontractors and smaller suppliers online. Access was obtained through data links encrypted for security. Importantly, access was made available before a design would be formally "released," or frozen, so that downstream users of the engineering information, such as those in manufacturing and quality control, could check that it met their requirements in a timely way. Backup databases were maintained at Boeing, Vaught, and GE facilities and were synchronized daily with that at Pico Rivera.

A crucial aspect of the database was the tight control of the process by which engineers could enter data. Engineers from the major subcontractors collectively defined 14 part families, each of which would share given attributes, and agreed on rigid modeling rules for defining lines, arcs, surfaces, and other basic geometries for these families. Examples of part families included composite panels, machine metallic parts, tubing, and electrical wire harnesses. Common approaches to modeling were valuable because even within the application software (NCAD and NCAL), a variety of options exist for modeling particular parts. Early in the B-2 program, engineers had found that without fixed modeling rules, it was very difficult to interpret data constructed by others. This made it difficult for other engineers to check for compatibility of their surfacing designs with interfacing parts, and to manipulate their models correspondingly. As a senior Northrop design engineer explained,

> The first F-5 reconnaissance aircraft (the "Tigershark") was designed on 2-D CADAM™. It was followed by another F-2-derivative program . . . and then by the F-20. Each successive program we learned. . . . The Tigershark was a disaster. When we implemented a 2-D CAD system, we thought it would be a productivity-[enhancing] drafting aid, and we hit that first problem where, if an engineer left, the guy next to him couldn't pick up his model and amend it. He didn't know how the guy had it constructed. There were too many variables. We learned from that and starting getting into these rigid design modes.

Another problem that arises when engineers create models using different design rules is that machine tools must be reprogrammed separately for each part type, implying higher programming costs, and more time lost to machine. An unusually high level of standardization in data definition, then—beyond that attainable from using common design software alone—was an important feature of the B-2 database. Such standardization was achievable partly because the major subcontractors had yet to sink significant investments into development of idiosyncratic design methodologies.

A set of "data filters" reinforced this standardization. These were batch programs that would process all data to be entered into the database, checking that models and drawings were constructed according to the modeling rules. For example, if some attribute of a particular part was undefined, or if an arc was defined in a nonstandard coordinate system, the program would prevent the data from being entered into the database. An engineer explained the importance of the data filters as follows:

> Prior to this [all-digital] approach we had 'engineering check' functions—they used to check the drawings that the engineers produced. They would look for drafting omissions, etc. [For the B-2] we put a whole new organization in place called 'Data Verification' which developed and ran the filters which would check the models for data content and producibility of the part. So we could check, using the system, whether the data was correct and complete enough to drive the automated downstream [manufacturing] processes.

Thus, the data filters served as automated mechanisms for assuring consistency in data formation within the part families. The "Data Verification" organization, staffed by roughly a dozen high-level engineers, replaced the older engineering check functions, which prior to the B-2 were carried out by many more low-level engineers, who checked engineering drawing for simple or superficial drafting errors or omissions. "Batch update" programs were another important aspect of the system. They served to update the database with new designs for parts, such as fasteners, that were used in multiple locations on the aircraft. This was important to ensure that updating was done comprehensively and in a timely way. A manager explained that

> A significant accomplishment [of the Data Verification organization] was the generation of a whole set of update utilities that

> could be run against the drawing database to automatically update the data based on some change coming through, making it unnecessary to have an engineer actually log on and modify the data himself. This saved an enormous amount of engineer's time and made sure that things got updated right.

This automatic updating ensured that engineers would always be working with the latest version of others models and did not have to rely on others to exhaustively update common part designs.

As mentioned above, the consistency, comprehensiveness, and integrity of the B-2 design database served larger development and manufacturing purposes. The major cost savings achieved with the systems that were most emphasized by engineers and managers were in the areas of prototyping and maintenance documentation.

Prototyping. Perhaps the most important productivity benefits of the product definition system stemmed from the fact that it allowed parts to be manufactured on automated machine tools using information directly from the database. Thus, data for 3-D models were translated into codes to run numerically controlled machines used to shape parts. Specialized tooling for the machines—such as cutting tools, sanders, and grinders—were also designed directly from the database. This was an example of very tight integration between computer-aided design and computer-aided manufacturing—an achievement that is unusual even today. The process eliminated a large number of usually crucial intermediate steps undertaken in aerospace development programs typical in the industry.

The steps are described as follows. As with the B-2, the conventional process starts with the creation of engineering designs using 2-D and 3-D CAD. But unlike the B-2, most programs require that the designs be printed out and digitized for separate scanning into a tool design system. Manufacturing tool designs must be separately developed and numerically controlled machines programmed to create a prototype master tool. From this a series of increasingly accurate prototype tools are machined: handspline, secondary, and production tools. The production prototypes are used to build a full-scale structural mock-up of the aircraft.

Creating a full-scale structural mock-up is a highly labor-intensive process. It typically involves engineers (acting as "lofters") laying out large pieces of mylar, on which they draw shapes by hand. From these they create templates on photo-treated metal, file the metal "header boards" back to the outer lines, and stack them up with rods to create a skeleton. Lofters then lay plaster molds onto the skeleton, and then pull off particular sections and create sand molds from them. Metal is then poured into the molds to create the aircraft's outer skins. The accuracy of the interfaces of the outer skins are determined by the closest possible distance between header boards and the hand-shaping of the plaster (typically one inch).

A parallel part of the mock-up activity is to develop a separate full-scale mock-up of the wiring and tubing layout on the aircraft. This shows, in physical form, the configuration of the electronic and hydraulic control systems. Such mock-ups are generally made from original engineering drawings made in 2-D or 3-D CAD. An engineer described the traditional prototyping and tooling processes at Northrop as follows:

> This was a very elongated process. We would do lots of iterations . . . before we got to the production airplane. This took a lot of cycle time, and it was fed by a lot of blueprints and paperwork and so on. In the B-2 . . . the tooling and prototype parts were all fed out and NC'ed [numerical-control tapes were created from the database]. This led to a significant reduction in paperwork, time, and so on. It really streamlined things.

In this way, the B-2 product definition system allowed the elimination of a large amount of prototyping activity. Manufacturing engineering drawing and machine codes were created directly from the database without physical rendering. The result was that parts could attain their theoretical values much more accurately and with many fewer rounds of tooling production. By eliminating intermediate tool prototyping steps and full-scale mock-ups, less room was left for design misinterpretation and reinterpretation, especially by downstream mechanics and manufacturing engineers. This was especially crucial for the sculptured surface parts, because extremely precise part descriptions were required to achieve consistency in the surface. (Recall that such consistency was necessary to meet the low-observability objective.) Since the data were defined very narrowly and consistently—with a high degree of conformity to the design rules—the function of translating designs into machine codes and then into parts became much less uncertain, and freer from errors caused by inevitable ambiguities in design specifications. Also, correcting errors that were detected was less costly, since incremental design changes could be incorporated at low cost. Northrop claims a 6-to-1 error reduction in form and fit error due to the system, a ratio that implies a tremendous reduction in redesign and reworking in the development process. This corresponded to a roughly 90% first-time fit ratio, with typical aircraft programs accomplishing an average of 50%. According to engineers, this was one of the most important benefits of the entire product definition system, without which the performance criteria of the aircraft, especially low observability, would have been reachable only at exorbitant cost.[4]

An example here is illustrative. The B-2, like many aircraft, used an extensive hydraulic system to control the ailerons used for rolling and banking, for example. Because the single-wing design of the B-2 did not include a tail, the burden on the ailerons to control flight was much greater than normal. The hydraulic tubing therefore had to be made of titanium, a material that could withstand very high pressures. Also, the tubing sections had to be cryogenically sealed together. Titanium is very stiff; once shaped, it cannot be reshaped. If it is out of tolerance, it must be scrapped. This is also true of the sealing. This implied that if the tubing was inaccurately fitted the first time, very high costs would be incurred in redesign. The product definition system facilitated the accomplishment of first-time fits for the hydraulic system.

It should be noted that failures of part fits apparently did occur despite the database. Scott (1991) reports that problems arose, for example, in fitting wire harnesses across sections made by different subcontractors. Some harnesses were initially the wrong length or gauge, or the bundle was incorrectly sized. The very dense cockpit wiring was apparently replaced three times (Scott 1991, p. 73). But managers maintain that such problems would have been much more frequent without the database.

Maintenance. Aircraft development programs must develop extensive maintenance manuals providing detailed part counts and information on a large number of part characteristics, such as location, material composition, and function. For advanced aircraft such manuals are millions of pages in length, and are very costly to develop. Traditionally, these manuals were written from copies of blueprints or the printed outputs of 2-D CAD systems and often required significant redrawing. Updating the manuals after design changes was also costly. For the B-2 project, maintenance and logistics personnel have continuous access to the centralized database, and can download updated information quickly. Data on particular "line-replaceable units" can be printed out as needed, although recently some have been able to use hand-held computers to access the data directly. Extensive paper manuals and redrawing have been avoided, with large cost savings.

Interpretation

It is clear from the descriptions that the product definition system allowed much better communication between designers, manufacturers and maintenance people than would have been the case without the system. First, it decreased the number of messages that needed to be sent between designers to achieve the goodness-of-fit targets. The systems allowed engineers to capture and transmit a large volume of data on part designs in a very economical way. Second, the system reduced the scope for misinterpretations of complex product descriptions by designers and by manufacturing engineers and machinists. It also facilitated downstream maintenance activities through automatic updating of the database. These benefits were realized by providing ways in which designers could create very precise part descriptions in 2-D and 3-D CAD and by providing common access to a shared database. The very narrow modeling and data content standards and the extensive automated data verification procedures played key roles in ensuring the precision, integrity, and utility of the database.

The following theoretical interpretation of the fundamental functions and benefits of the B-2 product definition system is based on literature from the economics of organizations and from IT/coordination theory. Implications of this interpretation for IT's impact on organization design and governance choice are also discussed.

A Technical Grammar. The B-2 product definition system was a technical "grammar" by which engineers and others conveyed information to each other. This grammar was established through the highly-developed and highly standardized data formation and modeling procedures of the system, which laid down well-defined rules for communicating complex information inherent in the part designs. I draw the analogy between the product definition system and a grammar because the system's rules can be seem as constraints on the ways that the basic building blocks of computer modeling (geometries, coordinate systems, etc.) could be combined to create part designs. The analogy to a grammar is closer than to a "language," because these basic building blocks—words, the units of meaning—were commonly used across the firms in question prior to the B-2. Thus, the B-2 system standardized not "words" but the rules according to which the "words" could be manipulated and combined.

Monteverde (1995) suggests that organizations exist partly because they provide the means for their members to engage in what he terms an "unstructured technical dialog." This dialog is defined as ". . . uncodifiable, generally verbal, and often face-to-face communication" (p. 1629), and is facilitated by firm-specific communication codes useful for transmitting informal and partly tacit knowledge between members of the organization. Following Arrow's (1974) emphasis on information channels as the basis for organizations, Monteverde (1995) argues that since these common communication codes are not available to independent firms wishing to exchange with each other, the ability to facilitate technical dialog is a key advantage of hierarchical organization relative to market-based contracting. One can interpret the technical grammar created by B-2 product definition system as precisely a system of communications codes useful for transmitting informal and partly tacit knowledge from one engineer to another—in this case information about the intricate details of part designs. In this way, the systems served to make a large part of the otherwise necessary "unstructured dialog" less necessary. It did this by constraining communication so as to remove the ambiguity which otherwise plagues attempts to codify partly-tacit knowledge. That is, the B-2 systems transformed *unstructured* technical dialog into *structured* technical dialog. In this way, the B-2 systems may have reduced the role for hierarchy in establishing and maintaining firm-specific communication codes, thereby allowing the project to be carried out in a vertically disintegrated way, with less hierarchical control.

The technical grammar, or communication codes, defined by the B-2 systems can be seen as a set of social conventions around which engineers coordinated their activities while acting relatively autonomously. The rigid modeling guidelines and data content standards functioned in a similar way to the way in which traffic signals and clocks operate to coordinate people's activities. Schelling (1978) originally used these examples to illustrate how certain agreed-upon technologies allow individuals to synchronize their activities without extensive exchanges of information between them. Thus, after traffic signals were introduced, "nobody needed tickets, schedules, or reservations to cross the intersection. All necessary instructions could be reduced to a binary code in red and green lights . . ." (p. 121). Traffic signals relieve drivers of the need to communicate their plans to each other at each intersection, thus lifting a heavy burden on drivers' cognitive processing capacity.

Clocks perform similarly: "I do not set my watch at zero and let it run through the day on the decimal system; I have a watch like yours, one that I coordinate with everybody else's at remarkably little cost" (p. 122). Watch-wearers have a common system with which to make appointments with each other, and thus avoid having to enter negotiations for a new system each time an appointment is desired. Of course, the B-2 system allowed very sophisticated messages to be sent, received and understood by engineers, and in that sense provided a much richer means of communication that traffic signals or clocks do. Like devices that allow simpler communication, however, the B-2 system acted as a social convention for coordinating activity.

A key feature of traffic signals and clocks is that they allow coordination to occur without the assistance of a third-party facilitator. Coordination is facilitated by reducing the volume of information flow that must occur "horizontally"—i.e., between coordinating parties—in order for coordination to succeed. This limits the need for a third party to facilitate the information flow, or to make decisions about how that flow should occur. Thus, coordination can occur in a spontaneous way. Some organizational economists, especially Malmgren (1961) and Milgrom and Roberts (1990, 1992), have postulated that a central economic role of management, or bureaucracy, is to act as a third-party information processor. The idea is that for coordination to occur with an organization, subunits must be made aware of the plans of other subunits in order that their expectations about each other's plans become consistent with an efficient equilibrium outcome. The problem can be posed as one of communication in a Prisoner's Dilemma-type coordination game. Recall that in that game, two prisoners have only weak incentives to cooperate with each other in denial, since they cannot communicate their planned strategies to each other. Milgrom and Roberts (1990) argue that by serving as an information channel between the "prisoner" subunits, central management can help achieve better coordination outcomes. Thus, understanding the B-2 systems as establishing a set of social conventions helps explain why the project succeeded without the need for continuous interventions from a central authority to promote coordination, and therefore why it allowed a significant decentralization of decision-making related to design. In particular, the system facilitated the formation of *convergent expectations* (Malmgren 1961) on the parts of engineers and managers in the various units and firms about design plans, reducing the need for extensive transmission of those plans by a third party such as a central authority.

An important benefit of decentralized decision-making emphasized by Milgrom and Roberts (1988, 1991) is that it weakens incentives for organization members to waste organizational resources attempting to lobby a central authority for decisions favorable to those members. The "influence costs" generated by such lobbying behavior are seen as constituting a fundamental limit to centralization, and to bureaucratic organization more generally. Schelling's (1978) examples of clocks and traffic signals illustrate how standardized technologies, by acting as social conventions, serve to limit influence costs. Schelling (1978) notes that there is no obvious authority to whom one can appeal if one is inconvenienced by a red traffic light at a particular moment or by the fact that it is now, say, 2:00 pm. As a result, few resources are expended in attempts to wring favorable decisions from a (human) authority.[5]

The scope for wasteful lobbying efforts was similarly restricted in the Stealth bomber project. The project was organized in a vertically-disintegrated way, with Northrop acting as the prime contractor to the U.S. Air Force, and the other firms acting as subcontractors to Northrop.

As such, Northrop did not enjoy hierarchical authority over the other firms. Its only leverage was the power of contract directive, which was subject to the interpretation and action of the courts. The design groups within the various subcontracting firms were certainly interested in design changes that would ease their workload without affecting their workshare or rewards. In the event, since Northrop's ability to impose design changes was contractually constrained, there were fewer incentives for the major subcontractors to expend resources lobbying the company for favorable treatment. As will be seen below, the Air Force apparently did act as an occasional intervening authority, and some incentives to lobby for favorable treatment therefore existed. Nevertheless, one can safely conclude that influence costs were probably much lower than they would have been without the product definition system, or with a less ambitious version of it. Thus, the technical grammar defined by the B-2 systems established a social convention which limited the need for a single hierarchical authority to intervene in crucial design decisions, and thereby limited what would otherwise have been significant scope for costly influence activity.

Agency/Measurement Costs. The B-2 product definition system clearly shares some similarities with Schelling's (1978) examples, especially to the extent that it served as a coordination mechanism which allowed the use of authority to be severely limited. Perhaps the major difference between the B-2 system and these examples is in the mechanisms by which they enforce compliance with the standards they also establish. Schelling (1978) points out that there is little incentive to operate on one's own timeclock or to ignore traffic signals. Thus, social conventions often do not require special incentive systems to encourage people to respect them. Failing to keep good time or to obey traffic lights often carries built-in penalties for the perpetrator. Ignoring traffic signals is hazardous, and especially so at rush hour. This is also when, from the point of view of coordination, it happens to be most important that drivers comply. Watches and traffic signals therefore achieve "planning without control."

The B-2 systems also achieved a form of automatic enforcement of standards, although the enforcement mechanisms contained elements of control. Recall that a key feature of the product definition system was that it contained "batch update" programs and "data filters" that served to automatically screen out designs that did not conform to the data formation rules, and to automatically update designs throughout the system. These features were important because they ensured the integrity of the database, reducing errors from inaccurate interpretation by engineers and mechanics of other engineers' designs. Some of these errors in data formation could have arisen from inadequate motivation on the part of engineers to conform to the technical grammar. Designers often face incentives to cut corners by failing to fully specify the construction of the data for a part, by using familiar but inappropriate modeling methods, or by failing to systematically update new designs. Each of these actions involves withholding valuable information from others. Similarly, manufacturers could strategically misinterpret part designs in order to shift costs onto others, fail to exert due effort, and attempt to evade responsibility for their own mistakes.

These kinds of opportunistic actions qualify as a type of agency cost, which arises when the incentives of a principal and an agent are misaligned. Jensen and Meckling (1976) define agency costs as the costs associated with self-interested actions by members of an organization, in addition to the costs associated with monitoring and metering the performance of those agents to limit such actions. The B-2 systems can be understood as reducing agency costs by preventing certain kinds of self-interested behavior by engineers, managers, and others, and by providing a relatively low-cost way of monitoring the quality of their work. But because the project was not carried out within a single organization (the setting in which the notion of agency costs was first applied by Alchian and Demsetz 1972) but rather in a network of independent contracting firms, the concept of "measurement costs" is more applicable. Measurement costs are agency costs incurred when a good is purchased through the market. Thus, when buyers cannot precisely determine the qualities of goods to be bought, and when sellers can cheaply, and with little risk of detection, reduce or misrepresent the quality of their goods, market contracting becomes hazardous (Barzel 1982; North 1981, 1991).

This kind of situation was present in the development of the B-2. Because measuring the quality of designs was far from straightforward, opportunistic or careless engineers could construct designs of inappropriate quality with relatively little chance of detection or sanction. In the absence of the information systems, it would have been extremely costly to monitor the qualities of the thousands of designs produced for the B-2. The product definition system, by serving to codify pieces of design data that would otherwise have been left tacit and hence open to interpretation, provided unambiguous measures of data quality. Also, each contractor could be confident that opportunistic actions by others would be prevented automatically. This can be interpreted as improving the *contractibility* of the information, which lowered the costs of monitoring the extensive subcontracting arrangements and metering the performances of suppliers.[6]

Existing theory identifies counteracting effects of IT on organizational structure. For example, Gurbaxani and Whang (1991) point out that by reducing agency costs, IT may allow more decentralization within organizations because it can be used to monitor and meter the performances of employees at lower levels. This allows decision rights to be placed where the most decision-relevant information resides, with less risk of self-dealing. On the other hand, they also argue that IT may simultaneously lower the costs of processing information up and down the hierarchy—so-called *vertical processing*—that would tend to favor more centralization. The net effect depends on the relative magnitudes of these two effects, which presumably depends on the features of particular information systems. In the case of the Stealth bomber, decentralization was arguably aided by reductions in agency/measurement costs, but other effects, notably reductions in costs of *horizontal* information processing—communication across groups of designers—allowed by the technical grammar function of the system, also contributed to the decentralized outcome. Any improvements in vertical information processing appear to have been offset by these other effects.

The theoretical link between agency/measurement costs and organizational boundaries is not clearly drawn in the literature. Thus, Barzel (1982) and North (1981, 1991) have argued that when an exchange involves large measurement costs, incentives are created to internalize the transaction, since market prices do not act as "sufficient statistics." This argument is not fully comparative, however, since agency/measurement problems presumably continue to exist with internalization, and the advantages of hierarchy over market contracting for governing these types of exchanges are not well-developed theoretically. Williamson (1985) suggests, however, that because firms possess greater powers to audit internal business units than do outside buyers, firm hierarchies can reduce measurement costs relative to market contracting by allowing better access to information relevant to the production of inputs, such as input quality. If this argument holds, once can conclude that the B-2 information systems, by limiting measurement costs, helped make viable the vertically disintegration of the project. The stronger conclusion, however, is that by reducing agency/measurement costs, the B-2 systems aided in the decentralization of the B-2 project.

Asset-Specificity. A clearer theoretical route by which the B-2 product definition system supported the vertically disintegration of the project is by reducing the levels of asset-specificity required by the project. According to transaction cost theory, market-governed exchanges are hazardous when asset-specificity is high because the party making greater specific investments may be "held up" by the other party in an attempt to capture the quasi-rents from those investments (Williamson 1975, 1985; Klein et al. 1978). In addition, one party could take opportunistic advantage of contractual terms during a contractual dispute to appeal to the courts for redress (Klein 1993). By contrast, the firm's hierarchy can as a last resort resolve contractual disputes by fiat, being assured that courts will forbear from intervening in internal disagreements between business units (Williamson 1991). Thus, large-enough reductions in level of transaction-specific investments associated with a given transaction will lead to market-based governance of that transaction, all else equal.

The improvement in communication afforded by the technical grammar function of the B-2 system led directly to a reduction in the level of project-specific investments made by the various firms. This was because the system transformed the design work in such a way as to radically decrease the amount of engineering effort the parties were required to commit to the project. Large amounts of engineering effort were saved that otherwise would have been expended on updating repetitive and nonrepetitive designs, developing manufacturing engineering drawings from original designs, creating separate codes for numerically controlled machines, developing several tooling prototypes, and building a full-scale structural and wire-and-tubing mock-ups of the aircraft. Also, parallel efforts in developing extensive maintenance manuals covering each part were avoided. Each of these activities would have had essentially no direct re-applicability to other aerospace programs because the actual tooling was entirely specific to the unique overall design of the Stealth Bomber for its quite idiosyncratic mission. Since this effort was essentially unusable if the project were to be delayed or canceled, it represented transaction-specific investment that resided in individuals' knowledge and skills—that is, human asset specificity (Williamson 1975).

The presence of human asset specificity was first found to be associated with hierarchical organization by Monteverde and Teece (1982). The firm in that study chose to make, rather than buy, those components for which the given level of human asset specificity was significant. In the case of the Stealth bomber, however, the level of human asset specificity for each part design, rather than being taken as given, was effectively reduced by the information system. The potential costs of holdup during the development process were thereby diminished.

Such holdups could have had a significant economic effect on the contractual partners because the contracts included stiff penalties for exceeding initial cost estimates. Thus, the viability of the extensive subcontracting organization of the B-2 development process may have been due in part to the role of the product definition system in reducing the costs of governing market-based contracts. Therefore, in this case the information processing and governance effects of IT interacted. The better information processing afforded by the technical grammar in turn improved contractual governance in the presence of human asset specificity. These interactions between communication and governance effects have not been elucidated in the IT/coordination literature.

It is important to note that not all investments in human assets for the B-2 project were B-2-specific. There were clear possibilities of indirect reapplication of some of the technological knowledge gained in the course of developing the aircraft. Indeed, the supplemental case material indicates that each major subcontractor had a strategy of reapplication. Taken together, these strategies apparently drove the division of design responsibility negotiated among them. Also, at the time that the Stealth bomber was first designed, the Air Force had expressed interest in a "stealthy" fighter plane that was eventually built by Lockheed. But the significant uniqueness of the overall design of the Stealth bomber limited these reapplications. This design choice determined, for example, the idiosyncratic nature of the electronic and hydraulic control systems designed by Northrop, knowledge of which has very limited value in bombers and fighter planes with more conventional fuselages and wings. The in-wing engines developed by GE also have not been repeated in other aircraft, etc. Thus, a significant portion of the required engineering investment for the Stealth bomber design was highly specific to that design, and the firms making this investment implicitly faced significant contracting hazards. Therefore, the reductions in firms' required investments afforded by the B-2 systems were arguably quite important in aiding market-based governance.

The Structural Analysis System

This section presents the second part of the main case material. Early in the development planning process, the major subcontractors agreed to use a computerized system known as NASTRAN for analyzing the structural integrity of the aircraft. Developed by NASA, NASTRAN at the time contained the most advanced structural engineering software available. This software is now widely used for performing analysis of large structures such as buildings, bridges, and military aircraft. The B-2 program was one of the early aircraft development programs in which the system was systematically used to analyze the structure of an entire aircraft for sizing. The structural analysis activity was to be overseen by what was called the Master Model Committee, which contained representatives of each of the major subcontractors.

NASTRAN was applied to the Stealth bomber roughly as follows. The structure of the aircraft was defined as a set of elements, or small segments of a structure, each with a given number of nodes. Each element was named and endowed with capabilities for sustaining certain "loads"—i.e., forces acting on it from different directions. The Master Model Committee defined nodes at the interfaces of the various aircraft sections. An important feature of the NASTRAN system was that once the interface nodes were defined, the system allowed each subcontractor to work independently on the structural analysis of the section for which it was responsible, so that daily communication between subcontractors was unnecessary. The element-based representations of various aircraft sections were then combined along these nodes to form the complete structure.

The combination process involved each subcontractor developing matrices of physical equilibrium equations for each element in its section. These equations took account of forces both internal and external to the structure. NASTRAN then simulated these forces, computed the natural frequencies of each section, and identified elements that were overstressed or understressed. Redesign that took advantage of the product definition system was then undertaken to stabilize the structure. Also, the program ensured that the surface lines of the various aircraft sections matched up. According to engineers, matching up the surface lines posed the most difficulties in redesign efforts.

Seven master models of the aircraft were run on a supercomputer, each containing more design detail than the last. Given the highly unique design of the aircraft, managers agree that many more iterations would have been necessary without NASTRAN. According to managers, the system did not significantly reduce the amount of initial design work that was performed. But it did significantly reduce the amount of redesign that had to be carried out to achieve the final version. According to the lead Boeing engineer on the project,

> Even with NASTRAN, we still had to do wind-tunnel testing and stress testing. But we went through fewer redesigns. And the redesigns were easier because the system pointed you right to problem. . . . The system was indispensable.

NASTRAN, however, does not include an algorithm that can yield the optimal design changes for given element stresses and line mismatches. It is not a problem solving "expert system." Any redesigns, or even direction for further design elaboration, had to be negotiated in the Master Model Committee. According to managers, the Committee was generally successful in resolving disputes that arose about sharing the burdens of redesigns as a result of NASTRAN analyses. But it could not resolve all disputes. One of these involved Vaught and Northrop. After an early model was run, significant redesign was required around the inner wing section and the crew station. It turned out that the change increased Vaught's share of the contract, while simultaneously causing the rate of return to fall to 3% as development costs escalated above original estimates. Vaught insisted on compensation from Northrop, but agreement on a figure could not be reached in the Master Model Committee. The matter was escalated to the program manager's office and then to the CEO level for settlement. There it dragged on for more than two years, until the Air Force's program director, Brigadier General Richard Scofield, was asked to intervene. The Air Force at that point apparently decided to compensate Vaught for some of its foregone returns by adjusting the contract *ex post,* likely by approving a late "engineering change proposal" as provided for under the Federal Acquisition Regulation. Importantly, while the dispute dragged on, the development work continued at essentially the same pace.

Such interventions to settle design change problems may have been more common in the B-2 project than managers are willing to admit, even today. Scott (1991) reports receiving a letter from a disgruntled B-2 employee while editor of *Aviation Week and Space Technology,* a trade publication. The employee claimed that "the Air Force often has to step in and settle disputes [among] bickering B-2 subcontractors" (p. 81). Interventions are not publicly discussed by company managers or by the Department of Defense, perhaps because they imply that Northrop, as the prime contractor, was unable to fulfill its formal contractual obligations. Indeed, the General Accounting Office's summary of the primary production contract states the following:

> Northrop is responsible for selecting subcontractors and *effectively managing the subcontracts* required to perform the work. Northrop is required to monitor the major subcontractors' performance and provide reasonable assurance to the Air Force that contract requirements will be met (p. 5; italics added).

Similar provisions were likely included in the still-classified development contract. In addition, it should be noted that the regulations governing the writing of all federal government procurement contracts—the 1984 Federal Procurement Regulation and the Contract Disputes Act of 1978—make no provision for a government agency to become actively involved in settling disputes between subcontractors. The dispute resolution procedures apply exclusively to primary contracts (see parts 33 and 43).

Interpretation

The descriptions suggest that an important consequence of the NASTRAN system was to enable the subcontractors to work fairly independently on the structural design work by "modularizing" the structure around several nodes. This effect is reminiscent of Hayek's (1945) emphasis on the value of decentralization in making efficient use of local knowledge. Hayek argued that economic progress is marked by the growing use of knowledge, but also by the diminishing importance of "knowing what others know." The "marvel of the market" is that it allows agents to coordinate with each other on the basis of simple price signals, thereby relieving them of having to exchange large amounts of information about preferences, costs, quality, etc. The modularization of the B-2 structure may have reduced communication costs by reducing the volume of information required to flow between the co-designers to achieve the goodness-of-fit objectives. In addition, NASTRAN clearly reduced the level of investment in specific human assets that would have been necessary in the absence of the system by producing significant savings from less redesign of the aircraft structure. It also reduced the uncertainty about the effective design constraints under which the major subcontractors were operating. This reinforces the interpretations above of the functions of the product definition system.

Like the B-2 product definition system, the NASTRAN system appears to have acted like a social convention, serving to reduce the volume of horizontal communication necessary to achieve coordination and limiting the role for hierarchical authority. While the NASTRAN system did appear to depend upon a "centralized" governance organization—the Master Model Committee—this Committee carried little hierarchical authority over the contractual partners. The NASTRAN system and the Master Model Committee together, however, did not entirely eliminate the role for hierarchy in helping achieve coordination on the design of B-2 structures. The dispute between Vaught and Northrop illustrates how the Committee operated to some extent in the "shadow of authority" cast by the Air Force. When the dispute could not be resolved in the Committee, the Air Force decided to absorb some of the governance costs of the subcontracts. This can help explain why no serious holdup occurred during the dispute; parties could rely on the Air Force to at least partially, safeguard their specific investments. It may also help explain how such broad and deep standardization could be achieved between the firms on features of the product definition system.

The Air Force's apparent willingness to intervene in the Stealth Bomber project therefore implies some limits on our interpretation of the B-2 systems as serving to decentralize decisions, and also limits our ability to generalize the arguments about the effects of information technology on firm boundaries to nondefense industries. The subcontracts in this case appeared to benefit from a dispute resolution mechanism short of the courts that business contracts generally do not possess. While it is not clear how frequent these interventions were, the Air Force was at least occasionally available as a last resort to adjust the "cost-plus" portion of the contract and partially override the "incentive" portion *ex post.* The Air Force may have been willing to do this because it is under less immediate pressure than private firms to reduce cost. The veil of secrecy behind which the Stealth bomber program was carried out may have further relieved such pressure. Thus, an informal but well-understood dispute resolution mechanism may have been present, placing the observed arrangements outside the bounds of "neoclassical" contracting governed by the courts (Macneil 1974). Indeed, the presence of such a governance feature may help explain the willingness of independent subcontractors to make significant investments specific to the B-2, even if they were at much lower levels than they would have been without the information systems. This suggests that the Air Force's role in this case may have enhanced efficiency, although influence costs were undoubtedly higher as a result. Thus, while the B-2 information systems clearly facilitated significant decentralization of decision-making and vertical disintegration, they evidently did not completely eliminate the need for authority during the course of the project.

Conclusion

In the broad sense, perhaps the most significant contribution of the B-2 information systems was that they allowed a very high-technology aircraft to be produced, which might otherwise have been impossible to develop. Indeed, the design features of the Stealth bomber—especially its "stealthiness"—demanded information technology well beyond hand-drawn blueprints, and even beyond the capabilities of most database and engineering systems circa 1980. In this case, the new information technology did not serve simply to lower the production costs of a given product, or even to allow new features to be added to that product. Instead, it allowed an entirely new kind of product to be designed and produced. This fundamental benefit of the B-2 systems was realized by the enhanced coordination afforded by the systems, in a situation where coordination was perhaps the central obstacle in managing the enormously complex project. Specific features of the systems—especially the "deep standardization," data filters, and updating features—were crucial in helping to solve the difficult communication and governance problems associated with the project. The deep standardization feature of the product definition system allowed the system to act as a technical grammar for communication. This grammar, which set precise rules for forming design data, promoted coordination by served as a social convention. The system also allowed designers to be continuously informed on each others' precise design plans, in an environment where the incentives for individual engineers to ensure the accuracy and timeliness of their plans in the absence of the system were probably not strong.

By setting a social convention and providing a communication channel between designers, the product definition system allowed considerable decentralization of design decision-making. The decentralization was possible because of the limited need for a central authority to assist in coordination efforts. This also restricted wasteful influence activities. The NASTRAN system operated similarly. However, the supplemental case material indicates that some centralization may have been required to achieve later decentralization. In particular, agreement on the kinds of detailed standards and definitions necessary for decentralized decision-making may have required the assistance of a central authority at the stage at which systems were being adopted. This would imply that in the absence of a central authority, independent firms may find it easier to agree to adopt so-called "off-the-shelf" software, rather than proprietary software.

The product definition system also reduced the costs of governing the exchange relationships between the firms engaged in the project. By creating a technical grammar for communication, the system reduced the amount of effort engineers had to make in developing the design, allowing it to be executed without the large project-specific investments in various prototyping activities, redesign routines and maintenance documentation usually necessary to accomplish these tasks. Reducing human asset specificity may thus be an important way in which IT favors more outsourcing or virtual forms of organization, as opposed to more decentralization within single organizations. In addition, the product definition system included special "data filters" and updating features that acted like automated mechanisms for monitoring engineers' design activities. These features helped ensure that data formation standards were adhered to, which controlled agency/measurement costs. These features also aided the decentralization of decision-making, though the implications for organizational boundaries are not clear.

The B-2 systems thus substituted for bureaucracy by improving governance and coordination through several well-defined economic processes. The case highlights a limitation, however, on the ability of agency theory to explain some of the benefits of the product definition system. Recall that in addition to preventing acts of opportunism, the system also helped prevent "honest mistakes"—errors a result of, for example, genuine misinterpretation of designs. Agency theory assumes that the agent knows the principal's objective, but can shirk because the principal cannot directly observe the agent's actions or type. However, when uncertainty is so great that the principal cannot precisely convey her objectives to the agent, the possibility of mistakes due to genuine misunderstanding may become more important than agency problems. In these situations, a B-2-type system may serve to motivate agents by helping to communicate the principal's objectives to them as much as by facilitating intensive monitoring of their behavior. It is difficult to judge which function of the system was more important from the case material.

The governance role of the B-2 information systems also sheds light on ideas about the organizational basis of virtual corporations. For example, Johnston and Lawrence (1988) and others envision virtual corporations as being governed primarily by trust relations between partners. Sociologists have emphasized trust as key element in economic relations (e.g., Gambetta 1988, Hamilton and Biggart 1988, Bradach and Eccles 1989). The Stealth bomber experience, however, suggests that once systems standards have been established, information systems can reduce the value of trust in exchange by helping to monitor contractual performance and resolve disputes. This applies to strong forms of trust in particular—that is, to trust that is unsupported by social or economic sanctions (Barney and Hansen 1994). While this kind of trust may be important in helping forge agreement on such standards in the first place, once standards are diffused, it may become less important as a source of competitive advantage. At the same time, advanced IT may open up new opportunities for competitive advantage at the level of strategic alliances, by forming the basis for superior interfirm coordination capabilities. This may be especially important when interfirm trust is difficult to create *ex ante,* such as when partners are new to each other, or when transactions span cultures. This would appear to be an important issue for future research.

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Endnotes

[1]The paper pays little attention to sociological variables such as trust (e.g., Gambetta 1988, Hamilton and Biggart 1988, Bradach and Eccles 1989) or political variables such as voice (e.g., Hirschman 1970). This choice of focus does not imply a denial that such variables were important in explaining project successes. Rather, it reflects an approach to case study research in which a particular set of theoretical lenses are applied to the material in order to further develop, and judge the range of application, of those lenses.

[2]A growing literature is exploring the role of knowledge considerations in the theory of firm boundaries (Demsetz 1988, Conner 1991, Langlois 1992, Kogut and Zander 1992, Argyres 1996). The Stealth bomber experience may lend some support to these considerations, but they are not a focus of the current study.

[3]Another possibility, however, is that the transaction costs involved in carrying out a four-way merger—legal costs, for example—were greater than those associated with governing contracts between the separate firms. Indeed, if the design and development of the B-2 is seen as a one-time project (albeit extending over six years) rather than an ongoing set of relationships, it was probably too small in value (relative to the firms' total business over the longer term) to justify a merger.

[4]One benefit of prototyping is that it generates feedback to engineers about the quality of their designs, providing them with learning opportunities (Adler 1995). The all-digital approach used on the B-2 sacrificed some of these opportunities. However, other learning opportunities were created through the use of computerized devices for precisely measuring parts. These devices produced data useful for the redesign of certain parts and can be seen as complementary to the product definition system.

[5]Hirschman (1970) argued that influence activities ("voice") can bring net benefits to an organization if market forces are not strong enough to motivate the organization to improve efficiency. The incentive features of the contractual structure under which the B-2 firms operated would suggest that the economic benefits of influence were outstripped by its costs in this case. However, the ease with which some changes in initial cost estimates were approved by the Air Force suggests that the forces encouraging efficiency were weaker than the contract suggests (see below).

[6]Bakos and Brynjolffson (1993) and Brynjoffson (1994) argue that adoption of advanced IT can lead to an increase in the importance of *noncontractible* investments. For example, IT adoption is often accompanied by increased demand for quality and innovation in inputs to production, both of which are noncontractible. In the B-2 case, however, adoption of the product definition system did not *cause* an increase in noncontractibility. From the design standpoint, the key noncontractibles (the most important of which was the low tolerance for

surface misfits) would have been equally critical if the information system had not been adopted. The noncontractibles were determined by the aircraft's mission and the overall design developed to meet the mission, not by the information system. It should also be noted that some IT systems, such as machine vision, do not necessarily require high-quality inputs, but themselves act to reduce defects (Argyres 1995).

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Endnotes

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