Architectural innovation in product development through early supplier integration

Kirkor Bozdogan[1], John Deyst[2], David Hoult[3] and Malee Lucas[4]

[1] Lean Aerospace Initiative and Center for Policy and Industrial Development, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[2] Lean Aerospace Initiative and Center for Policy and Industrial Development, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[3] Formerly, Department of Mechanical Engineering and Manufacturing Institute (retired), Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[4] TRW Space & Defense Division; formerly Lean Aerospace Initiative, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

The paper explains how an important opportunity exists to pro-actively integrate suppliers at an early stage in the concept exploration and definition stages of product development. Research suggests that the concept of architectural innovation can be extended so that product features are matched with the associated specialized technical skills of partners in the development team.

In addition to the establishment of integrated product teams, key enablers include: long-term commitment to suppliers; co-location; joint responsibility for design and configuration control; seamless information flow; and retaining flexibility in the definition of system configuration. Important contributing factors include: supplier-capability-enhancing investments; target costing; and incentive mechanisms. To promote innovative outcomes in military and government programmes, attention is drawn to the importance of governments championing closely-knit customer-supplier relationships.

Firms can build enduring competitive strength by leveraging the specialized knowledge bases of their supplier networks. Two case-studies provide lessons to improve current approaches to the creation of long-term partnerships, or strategic alliances, with suppliers.

1. Introduction

This paper presents initial findings from on-going research on early supplier integration into product development, undertaken under the auspices of the Lean Aerospace Initiative at MIT.[1] The Lean Aerospace Initiative (LAI) represents a significant commitment by both industry and government to develop a body of knowledge that can lead to substantial productivity improvements in the US defence aerospace industry as well as in federal government acquisition of military aerospace systems.

Initial empirical evidence from the defence aerospace industry suggests that up-front supplier integration into the prime (customer) company's cross-functional design team, as early as during concept exploration and definition stage, can foster architectural innovation in product development, resulting in a fundamentally new configuration of how the components in a product or system are linked together. Such a result, offering not marginal but significant improvements, can be realized by exploiting the technology base existent over the supplier network. Preliminary evidence indicates that early supplier participation can provide a major source of competitive advantage to firms proactively pursuing policies and practices fostering architectural innovation.

2. Early supplier participation in product development

This research was stimulated by earlier contributions which stressed the importance of production networks and cooperative interorganizational relationships as a key source of competitive advantage, where competition between firms is replaced by competition between networks (Thorelli, 1986; Jarillo, 1988; Gerlach, 1992; Provan, 1993). An important idea is that of *embeddedness*, referring to the connectedness of a supplier to a focal organization (prime), as well as to other network suppliers, either directly or through the prime. When a supplier's embeddedness in a network is strong, displaying a high degree of interdependence, opportunistic behaviour is sharply constrained while conditions for cooperative behaviour are fostered. In well-established networks, when outcome interdependence is high, members can be expected to suffer short-term sacrifices, not consistent with their immediate interests in return for expected long-term strategic advantage (Provan, 1993, p.843).[2]

Other findings have identified partnerships and alliances with suppliers as an increasingly important strategy for firms to develop and maintain competitive advantage (Dyer and Ouchi, 1993; Nishiguchi, 1994; Gulati, 1996). Previous research has also stressed the central role played by unilateral commitments in explaining the success of strategic alliances (Gulati et al., 1994), while others have concentrated on the importance of interorganizational collaboration and networks of learning, particularly in the context of markets characterized by rapid technological change (e.g., Powell, et al., 1996). Further, suppliers have been identified as an important source of innovation (von Hippel, 1988).

Other researchers have documented that allowing suppliers greater design responsibility represents an important factor in the superior performance enjoyed by the Japanese auto companies in product development (Clark, 1989; Clark and Fujimoto, 1989; 1991), in terms of both lead time and cost. It has been found that, in the Japanese system, suppliers are an integral part of the product development process: they participate early in designing new products, assume significant design responsibility, have strong communication links with their customers, and are involved in joint problem solving tasks. Moreover, it was found that, compared with their European and American counterparts, Japanese auto makers rely on their suppliers for a greater share of 'black box' parts and enjoy the additional advantage of being able to use a higher fraction of unique parts by relying on the engineering capability of their suppliers without incurring the disadvantage of increasing their own internal engineering workforce. (See, for example, Clark, 1989, pp. 1248–1252.) These findings indicate that the Japanese auto companies have integrated their engineering activities, wherein the efficiency of the assemblers depends on the efficiency of their suppliers and wherein what matters is the efficiency of the whole system rather than the efficiency of the individual groups (Clark, 1989 p. 1256). These findings also suggest that a significant source of the competitive advantage held by the Japanese auto companies derives not only from the extent of supplier involvement in product development but also from the quality of the customer-supplier relationships and the way these relationships are managed.

Building on these findings, additional contributions have attempted to define the supplier role in product development (e.g., Kamath and Liker, 1994; Ward et al., 1995; Liker et al., 1996; Virag and Stoller, 1996), while others (Brown and Eisenhardt, 1995) have underscored the importance of information networks for effective product development, along with planning and process methodology. More recently, it has been suggested that large savings in product development arise from ensuring database commonality with suppliers, along with early supplier integration into the customer company's integrated product development teams and allowing suppliers to play a role in defining product architecture (Hoult, 1997).

These results have highlighted the importance of closely-knit customer-supplier networks for establishing competitive strategic advantage. The findings indicate that collaborative problem-solving, information sharing, cost-sharing, risk-sharing and interorganizational learning are significant attributes of such networks. In particular, they identified efficient product development, through greater supplier participation, as a primary means of establishing strategic advantage. The evidence indicates that such closely-knit collaborative arrangements with suppliers have helped augment and expand the information network, as well as the technology and knowledge base, available for product development. These more specific contributions on the role of suppliers in product development were obtained mostly from research focusing on the auto industry, particularly the Japanese auto industry which is widely viewed as the role model for other industries as the main source of lean production principles and practices.[3] A more detailed review of these results would hence be helpful in developing a more complete understanding of the supplier role in this very important industry. It would also help delineate more sharply the specific contribution of this paper, which concentrates on the aerospace industry. Two sets of results, in particular, are worth outlining in more detail.

First, it is reported that a closer look at product development by the Japanese auto companies reveals an incomplete earlier understanding of the role played by suppliers. That is, contrary to the widely-held belief that Japanese manufacturers have created close partnerships with virtually all of their first-tier suppliers, they actually have such relationships with only a handful of their suppliers while the rest are assigned varying levels of responsibility and play more limited roles. Also, suppliers face fierce competition from others, but once a supplier has been awarded a contract for a part, it can normally expect to retain that contract for the life of the model. According to one study, most of the suppliers are chosen after completion of detailed design, before the first prototype (Cusumano and Takeishi, 1991, p. 573). Typically, suppliers face a clear but small window of opportunity during the concept stage, prior to the release of specifications, when they can suggest new technology or offer new methods. That is, they operate in a highly structured product development process which allows suppliers to be innovative within fairly well-defined boundaries. Those with more mature, partnership, relationships with their customers are given more flexibility, but even here they are provided specific design targets and are mostly asked for modest improvements.[4]

More recent research based on a survey of automotive component suppliers in the United States and Japan largely corroborates these findings. It is found that in both countries first-tier suppliers responsible for subsystems have higher levels of involvement in design and enjoy greater autonomy compared with other first-tier or lower-tier suppliers.[5] It is also found that, in Japan, the level of partnership and trust described in the literature applies mostly to first-tier suppliers responsible for complete subsystems and that, more generally, Japanese auto makers seem to employ various other methods (e.g., target prices, performance monitoring, competition, asset-specific investments, equity ownership, mutual dependence) to control their suppliers. It is further found that, in Japan, even when major suppliers are delegated design responsibility, they are given specifications formally, are required to design to these specifications, and are expected to develop and submit prototype designs on time (Liker et al., 1996 pp. 79–82).

Even though Japanese suppliers, on average, seem to have greater responsibility for more complex systems and a higher percentage of them design parts themselves rather than jointly with their customers, it is found that in general US suppliers have comparable levels of responsibility for design, analysis, prototyping and testing. US suppliers are also found to be just as likely to influence the requirements for the components they design and build, receive specifications that are no more restrictive, have design capabilities comparable to those of their Japanese counterparts, and communicate even more frequently with their customers in the early stages of the design process (Liker et al., 1996, p. 84). In fact, evidence suggests that a growing number of firms outside Japan have adopted product development alliances that employ many of the characteristics of the Japanese model. Among these, Chrysler has been cited as a notable example (Kamath and Liker, 1994, pp. 168, 170).[6]

However, it is difficult to draw a clear picture from these findings as to the nature and extent of joint design and development between major auto companies and their key suppliers. On the one hand, it is suggested that the very few first-tier suppliers, enjoying trust-based long-term partnerships with their customers, often participate in planning a new model or in determining, during the pre-concept stage, the specifications for parts or subsystems for which they are assigned responsibility (Kamath and Liker, 1994, p.158.). On the other hand, it is also suggested that typically suppliers are given specific requirements and are asked to go off and design to those targets, but without being specific about the varying roles played by different types of suppliers (Kamath and Liker, 1994, p. 167; Liker, et al., 1996, p. 85). Meanwhile, it is asserted, for example, that a greater percentage of subsystem suppliers have designed parts themselves rather than jointly with their customers (Liker et al., 1996, p. 84). More specifically, it is also asserted that suppliers are less likely to design their parts jointly with Toyota, while Toyota itself either designs the parts and provides blueprints to suppliers or uses its design-in process, which allows suppliers the autonomy to design their own parts subject to Toyota's specifications and constraints (Ward et al., 1995, p. 47).

These findings do not necessarily contradict other research results showing more direct evidence of customer-supplier collaboration in designing new products (e.g., the common use in Japan of 'resident engineers'). 'Resident engineers' are sent by key suppliers to customers' facilities to work as part of the customers' cross-functional teams in order to help solve design problems and attain target costs (see Nishiguchi, 1994, p. 131). At the same time, however, neither set of findings appear to shed clear light on the dynamics of collaborative design involving customer companies and their key suppliers. Finally, these findings are reasonably consistent in pointing out that lower-tier suppliers are typically used as low-cost production platforms and do not appear to play any noticeable role in the design process.

Thus, a major motivation for the research reported here is the apparent limitation of the existing literature in explaining the dynamics of joint product design and development, involving both customer companies and their suppliers. This topic is also of considerable conceptual interest, since existing theory, based on transaction-cost economics, essentially predicts that the design of complex, highly-customized, parts will be performed in-house rather than being delegated to outside suppliers. Several reasons are given for such an outcome. Transaction-cost economics (Williamson, 1975, 1989) asserts that minimization of transaction costs is a major concern of organizational design, where the main conclusion is that vertical integration is more likely when transaction costs are high. Under transaction-cost theory, manufacturers face basically two options: 'make' the part in-house and employ bureaucratic managerial mechanisms for internal coordination and control, or 'buy' the part from an external supplier and rely on the efficiency of the market to set prices. A key concern is that buying from an outside supplier could involve high transaction costs, in addition to potentially exposing the customer firm to self-interest seeking opportunistic behaviour by suppliers who cannot be trusted and who are likely to exploit any competitive advantage they can develop. It is argued that both greater product complexity and technological uncertainty favour making a component in-house, since both are likely to increase the cost of writing fully-specified contracts which would result in higher transaction costs compared with the option of doing the design and production work in-house at lower coordination costs (Masten, 1984). A key problem here, where transaction-cost economics provides little help, is one of incomplete contracts. Typically it is difficult to develop *ex ante* contractual formalizations, since there exist no well-established theories of complexity or of corporate decision-making under unforseeable contingencies due to technological uncertainty (see Tirole, 1990, pp. 29, 33).

Similar inferences can also be drawn from agency theory, which shares several assumptions with transaction-cost theory (e.g., bounded rationality, self-interest seeking behaviour, risk averse agents). However, agency theory, which provides useful insight into a wide variety of economic relationships, also provides a broader conceptual framework to help explain the observed customer-supplier interactions in design and development, through the design of the appropriate economic incentives. Broadly speaking, agency theory focuses on situations where the 'principal,' such as a customer company, delegates design responsibility to an 'agent', such as a supplier, and faces the problem of designing a compensation system (a contract) which motivates the agent to act in the principal's interests (Stiglitz, 1989; Eisenhardt, 1989). Because of the asymmetry of information available to both parties, the agent's actions are neither observable nor can they be inferred with certainty by the principal, based on observable facts or factors. This gives rise to the principal-agent problem, which is the central problem of economic incentives. Thus, the potential for being able to design appropriate incentive mechanisms provides the important explanatory link between existing theory and the observed outcomes summarized earlier.

In this paper we seek to develop an improved understanding of joint design and development, involving both customer companies and their suppliers. We strive to define the more specific conditions under which such collaborative behavior can foster architectural innovation (Henderson and Clark, 1990) in product design and development. Thus, the contribution of this paper is to carry the previous findings further, by analysing the dynamics of architectural innovation in product development over the supplier network. We have been led to the notion of architectural innovation over the supplier network through prior exploratory research on integrated product and process development teams, as well as on the impact of database commonality, in product development both schedule and cost. A major finding from this research, which quickly led to the idea of architectural innovation, was that seamless information flow linking the prime contractor with its suppliers, within the larger context of integrated product teams involving early supplier participation, facilitates innovation in product development.

The notion of *architectural innovation* (Henderson and Clark, 1990) was originally framed within a single-firm context and identified as an important source of building competitive advantage. *Architectural innovations* were defined as those that 'change the way in which the components are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) as untouched' (Henderson and Clark, 1990, p. 10). A component is defined as 'a physically distinct portion of the product that embodies a core design concept … and performs a well-defined function.' (Henderson and Clark, 1990, p.11.) Henderson and Clark offer a framework which classifies product innovations into four distinct types: *incremental, modular, architectural* and *radical*. Their framework has two dimensions. The horizontal dimension depicts the innovation's impact on existing technology underlying the components in a product (i.e., whether the existing technology is further reinforced or overturned). The vertical dimension traces the innovation's impact on product architecture (i.e., linkages between the components; whether the existing linkages remain largely unchanged or they are in fact changed). Thus, *incremental* innovations cover those cases where the existing technology is further reinforced, resulting in relatively minor changes in the technology content of the product while the linkages between the components remain unchanged. Examples include improvements in the power of a motor or in blade design for an electrically powered ceiling fan. *Modular* innovations cover those cases where the existing technology is overturned but the linkages between the components remain unchanged (e.g., replacement of analogue with digital telephones, electronic engine controls in diesel engines). In the case of *architectural* innovations, further exploitation of existing technology (e.g., materials, tooling, manufacturing processes) enables changes in product architecture. Examples include portable copiers, front wheel drive cars, and introduction of the proximity aligner in semiconductor manufacturing. Finally, *radical* innovations cover those fewer cases where an entirely new set of scientific and engineering principles overturn existing technology, revolutionize product architecture, and open whole new applications, markets and even new industries (e.g., radar, jet engine, microprocessor). (Henderson and Clark, 1990, pp. 10–13.).

Our research extends the architectural innovation concept to the inter-enterprise context, focusing on customer-supplier networks. We attempt to show that the cooperative customer-supplier relationships most conducive to the fostering of architectural innovation are those that are, at their core, characterized by shared responsibility in design and configuration control, within a virtual team environment. We concentrate on architectural innovation, through early supplier integration, to draw attention to the fact that relatively small technological improvements, by exploiting the technology base over the supplier network, can make it possible to create a new product architecture, resulting in significant benefits. Our emphasis on architectural innovation places a premium on the exploration of new possibilities in product design and development through proactive assimilation of new technical knowledge by working closely with suppliers. We believe this represents an essential strategic dimension of technology supply chain design and management (Fine et al., 1995).

We define 'architectural innovation through early supplier integration' to be a major modification of how components in a product or system are linked together, by proactively leveraging and integrating the technology base of the supplier network (key suppliers, tooling suppliers, subtiers) early in the product development process. Furthermore, we suggest an extension of the concept of architectural innovation to allow for two concurrent and interrelated changes which we believe are integral to the concept of architectural innovation: a significant modification in product architecture as it has been further defined recently (Ulrich, 1995), which is already recognized in the original framework, and a significant redefinition of workshare arrangements among the participants, in light of the new way of partitioning system elements and interfaces, to reflect a more effective utilization of the respective technical capabilities of the participants. In essence, the *tacit* (i.e., uncodified, experience-based) technical knowledge, resident over the supplier network, is exploited to the mutual advantage of the prime and its suppliers in the sense of a cooperative positive-sum game. Each member of the team supplies those portions of the product or system for which that member is best qualified. The result is a product development process wherein the key product elements and areas of responsibility are reconfigured in a manner that would not have been possible in the absence of such supplier participation, and where the outcome is significantly improved product development performance in terms of shorter cycle time, reduced cost and better quality.

The process is characterized by shared responsibility, on the part of the customer-supplier design teams, for technical design and configuration control and the process is unconstrained by prior contractually-agreed-upon workshare arrangements. Furthermore, the best practice is when the customer-supplier and supplier-supplier interfaces are allowed to change freely to optimize the system being developed. The empirical evidence provided here shows that these customer-supplier teams are integrated through seamless information flow, open communications, knowledge-sharing and appropriate incentive mechanisms. Both the prime and the suppliers are incentivized through flexible contracting and long-term relationships, following an initial competitive supplier selection process. They are thus motivated to share risks as well as gains while their proprietary technologies and business practices are protected through long-term strategic agreements and incentive systems. This is in sharp contrast with the traditional arm's length 'model,' characterized by rigid 'form-fit-function' interfaces between the prime contractor and its key suppliers, as well as between the key suppliers and the lower-tier suppliers. Under the traditional model, technical design specifications reflecting the customer's requirements are essentially communicated vertically without prior consultation, and interfaces are totally defined and controlled by the prime.

3. Architectural innovation with suppliers in the defence aerospace industry

The research summarized here draws upon field interviews, surveys, and case studies, focusing on both the defence aerospace industry and government organizations. Based on a survey of product development in the US defence aircraft industry, it was found that in 75% of the 40 military acquisition programmes surveyed suppliers were involved early in the design and development of major components.[7] However, their involvement was found to be lower for subassemblies (40%) and even lower for parts (20%). These findings support earlier informal observations suggesting that while key suppliers with major subcontract responsibility are involved early in product development, even before contract award, those supplying subassemblies and parts are involved early often for technical consultation on a variety of design issues. Another implication of these findings on subassembly and parts suppliers is that they are mostly selected in later stages of product development, such as after detailed design.

Traditionally, the role of suppliers in this industry is limited to manufacturing parts to the prime's technical design specifications ('build-to-print'). However, in recent years suppliers have been assigned greater design-build responsibility for major components and subsystems. They may also, in some cases, work jointly with the prime on integrated design-build teams. The delegation of greater design-build responsibility to key suppliers is part of a larger structural transformation in customer-supplier relationships, as many organizations have downsized and streamlined their supplier bases and have reassessed their make-buy strategies in an evolving new marketplace dominated by industry consolidation and increasing international competition. Our survey results indicate that suppliers were directly involved as team members in designing major components in 68% of the 28 programmes surveyed, where the prime contractor had established integrated product teams (IPTs). However, their participation in IPTs was much lower for subassemblies (21%) and even lower for parts (11%). The comparatively lower incidence of IPTs focusing on subassemblies and parts generally suggests the possibility that the industry may be depriving itself of the potential benefits that can derived from the use of IPTs in these latter contexts. On the other hand, these findings also suggest a more rigorous research approach to a determination of where the use of IPTs would offer the greatest benefits, taking into account optimal ways of partitioning product architecture and also considering costs of coordination.

Survey results further provide strong evidence for the finding that early supplier participation in IPTs, in military development programmes, substantially reduces the likelihood of cost-related requirements changes, subsequently during the demonstration and validation (DEMVAL) and engineering and manufacturing development (EMD) phases, driven primarily by producibility problems.[8] In light of these earlier findings, our case studies have concentrated on major components, developments employing IPTs, in order to create an improved understanding of the effectiveness of IPTs involving suppliers, with particular emphasis on the conditions fostering innovations in product development.

The survey findings prompted further investigation, in the form of case studies, which provided empirical evidence that early supplier integration is an important enabler of architectural innovation in product development. In one case it was found that a novel approach to contracting by the US government was instrumental in fostering close relationships between the prime contractor and its key suppliers. The resulting team effort created a new approach to the definition of the product's architecture, achieving significant reductions in both cost and cycle time. Specifically, unit cost was reduced by 75% and cycle time by 33%, while product quality was much improved (i.e., reduced parts count, increased reliability, reduction in heat management requirements, greater vibration tolerance).

Interviews also prompted a second case study which found that early supplier involvement in a prime contractor's integrated product teams had resulted in new design, fabrication and assembly methods and processes which significantly reduced development costs, as well as risks, while improving overall product performance and quality. In this case, the development cost of the new generation subsystem was reduced five-fold, compared with that of the last prototype unit developed during the previous phase of the programme, and product quality was much improved. The improvement in product quality, including greater performance reliability, maintainability and longer service life, resulted from the elimination of a major weld cracking problem, where welding was the previous method of choice for joining the various subsystem components. Another outcome was a significant reduction in risk associated with fabrication, as well as much simpler and less expensive manufacturing processes. In this case, cycle time reduction was far less important than subsystem performance and affordability considerations. Also, meeting the exacting subsystem performance requirements resulted in important technological improvements (e.g., in bonding, riveting, coating and cooling technologies). The latter case also exhibited open communications and knowledge-sharing within the integrated customer-supplier team, as well as joint configuration control, accompanied by a determined effort on the part of the government to reduce unnecessary and costly military specifications and oversight requirements.

These two product development efforts, involving rather complex but quite different systems, were examined in more detail in order to develop a better understanding of the critical institutional and organizational approaches, key processes, barriers, enablers and major outcomes. The discussion below concentrates on these two specific case studies, presents key findings, and summarizes major conclusions.

3.1. Case study A[9]

Initial field interviews with the personnel of a government System Program Office (SPO), as well as with the personnel of a major aerospace company serving as the prime contractor for that SPO, revealed what appeared to be an innovative teaming arrangement between government and industry. An extensive case study of the programme was performed in order to document the process and to determine its results.

The system development portion of the programme consisted of two major phases. Initially there was an industry-wide request by the government for proposals. The government reviewed the proposals and two contractor teams were chosen to design, develop and demonstrate competing system prototypes during the first phase of the programme. At the end of this phase a downselection process was performed to choose one contractor for engineering and manufacturing development (EMD) during the second programme phase. The research reported here focuses primarily on the first phase of the programme, wherein two competing teams developed and demonstrated system prototypes. More specifically, the research effort concentrated on the contractor team that won the competition in the first phase and was selected for the EMD phase and for eventual full-scale production.

At the beginning of the first programme phase the government faced a difficult dilemma. There was a strong and broad-based desire to take an IPT approach, while at the same time maintaining effective competition between two contractor teams. Previous experience seemed to indicate that an IPT approach would hamper an impartial competitive selection process. To address this issue the government created a contracting approach which is very different from the traditional adversarial model. In the traditional model the relationships between government and the prime, as well between the prime and suppliers, can often be characterized as being 'at arm's length'. For this programme the government and contractors were able to reshape these relationships so that they much more closely resembled goal-congruent partnerships.

The process of forming goal-congruent relationships was driven by a combination of factors including competition, a government commitment to a long term programme, and an atmosphere of open communication and trust. Competition had a strong influence because each contractor team realized that at the end of the first phase there would be a downselect and only one team would go on to EMD. The long term commitment meant production of 40,000 systems over a ten-year period at a total projected cost of about \$3 billion. Communication and trust were established by placing government representatives on each of the contractor teams. These groups of government representatives, called advocacy teams, were tasked with helping the contractor teams achieve performance and affordability goals and they also provided direct links between the contractor teams and the government programme office.

There were a number of additional factors that set the programme apart from other military programmes of comparable size and complexity. The government allowed a significant reduction in the number of requirements imposed on the contractors. By carefully evaluating the actual needs of users, the government was able to reduce the major requirements down to only six simply stated 'live-or-die' requirements. Additionally, there were large reductions in the number and form of military specifications and reports required. The prime contractor was given almost total configuration control of the system and in return the government received an extended warranty on system reliability and performance. Other reductions included smaller proposals, abbreviated statements of work, and decreased programme office staffing levels.

Perhaps the most significant aspect of the contracting approach was a strong emphasis on cost. A rather simple measure of cost, the average unit procurement price (AUPP), was established as the primary means of evaluating costs to the government. AUPP is defined as total programme cost divided by the number of units produced. AUPP turned out to be an extremely effective way of quantifying costs in a simple and straightforward fashion. The combination of AUPP and the six live or die requirements created a concise and clearly understood set of criteria for evaluating the two contractor teams.

As the programme evolved the strong competition between teams stimulated a vigorous search for cost-effective solutions to design tradeoff problems. Detailed analyses of the producibility of designs indicated that the cost of producing the highly partitioned architecture of the original conceptual design could be significantly reduced by increasing the levels of integration of various system modules. This trend toward integration was especially significant for the electronics portion of the system, which represented a large percentage of the total system cost.

Of particular relevance was the fact that suppliers were responsible for a major share of the electronics portion of the overall system. Within these supplier organizations resided the detailed knowledge necessary for increased integration. In effect, the electronics architecture had to be redesigned, in order to achieve the desired greater level of integration, and supplier knowledge was essential for the task. Furthermore, greater integration also meant that some portions or functions of the system, initially allocated to one supplier, might be reallocated to another. Hence, an increased level of integration meant that some trading of workshare among the suppliers would be necessary, along with changes in the levels of revenue they might expect, if the desired cost reductions were to be realized. Thus, some would lose, others might gain, and individual goals would have to become subordinate to team goals.

The strong competition and cohesive team approach created an environment by which a high level of integration could be achieved. Suppliers that lost some of the initially agreed-upon work assigned to them were able to relinquish potential income for the overall good of the team and the overall team's win strategy. A policy of total open communication allowed suppliers to bring their knowledge and expertise directly to bear on the cost reduction problem, resulting in a highly integrated electronics architecture. For example, in one instance some functions resident on a receiver module from one supplier were moved to an antenna module initially assigned to another supplier. This allowed the use of less expensive elements on the antenna module and reduced the production costs of the receiver module as well. Also, greater integration allowed the elimination of connectors and wiring harnesses which not only reduced costs but also increased reliability. A number of modules and associated connectors, as well as wiring harnesses for the on-board computer, were reduced down to a single circuit module with an end-connector. Other beneficial changes included reductions in heat management requirements, inherent electromagnetic shielding, better design for manufacturing and assembly, greater vibration tolerance, and a reduced parts count.

These and numerous other innovations had a dramatic effect on AUPP. Without the base of knowledge and collective expertise brought to bear on the problem by the suppliers, the prime contractor would not have been able to achieve the level of integration and design innovation finally realized, in a timely fashion. The gains were achieved not only by changing the manner in which modules were arranged and interconnected but also by changing the content of work performed by each member, relative workshare proportions, design responsibilities, and interfaces among the team member organizations. In this instance, the architectural innovation enabled by suppliers contributed significantly to a 75% reduction in AUPP, from initial estimates to final negotiated contract. In addition, the total system development and acquisition cycle time was reduced by 33%.

The case study specifically identified a number of factors which contributed to architectural innovation. The novel source selection process, along with the formation of advocacy teams, proved to be important precursors of subsequent innovative approaches. A very important unifying factor was goal-congruency, linking together the government advocacy team, the prime contractor, key suppliers and subtier suppliers, enabled through innovative contracting. Other major drivers were the limited scope of the acquisition, exemplified by six 'live-or-die' requirements, as well as the strong emphasis on AUPP. The winning team exhibited a high degree of open and candid communications. Suppliers became full team members and active participants in formulating plans and win strategies. An inherent part of the team building process was the establishment of a long-term programme commitment by the government and complementary long-term relationships between the prime and its key suppliers. The government also gave the prime contractor configuration control in return for an extended warranty. In turn, the prime passed down design authority and configuration control to the suppliers, greatly reducing reporting and oversight requirements. In a number of instances commercial practices were substituted for military specifications and reporting requirements were substantially reduced. Finally, innovative contracting methods also served to protect proprietary commercial pricing methods and trade secrets of some of the suppliers.

3.2. Case study B

This study concerned a major military subsystem that must function in a severe environment and over a broad range of operating conditions. With extremely high and exacting tolerance requirements, the subsystem is expected to operate satisfactorily at very high levels of temperature and vibration, and over a broad range of varying temperatures as well. Performance under such conditions accelerates metal fatigue, presenting particularly difficult and complex design, manufacturing and assembly problems. In addition, the design, manufacturing and assembly operations, and materials choices are tightly intertwined.

During an earlier developmental stage, spanning a number of years, the subsystem had gone through several generations of design, each one representing a radical departure from the previous one in terms of the specific materials utilized, technologies applied, and processes employed. During this earlier phase, the prime contractor had taken virtually total responsibility for all technical design and engineering tasks and suppliers were expected to 'build-to-print.' While these earlier generations of the subsystem generally exhibited significant technological evolution and improved system performance, they failed to deliver an acceptable product in terms of cost, schedule and technical performance. More specifically, none of these earlier systems, involving precision welding as the primary method for joining the various components, resulted in a viable product. The extremely high and varied operational temperature environment caused persistent cracks in the welds, foreshortening the useful life of the system.

In the next stage of the development process, the prime contractor adopted an entirely new approach, opting for greater involvement of key suppliers in the design process. An early choice was to design and build the whole subsystem in-house, since the prime contractor possessed all of the necessary critical technical skills and capabilities. However, a make-buy analysis revealed that the prime contractor could achieve considerable cost savings by delegating substantial design and manufacturing responsibility to its suppliers. A key deciding factor was whether the prime would be willing to make a significant investment in new technologies when one of the suppliers already possessed the capabilities such an investment would have created.

Consequently, through an initial competitive selection process, the prime identified two suppliers for each of the four components of the subsystem. The next step was to form collocated design teams, and execute designs which served as an elimination round prior to a downselection process. The prime then formed collocated integrated product teams with the winning subcontractors. These integrated prime-supplier design teams were given joint responsibility for design and configuration control. The teams, linked together electronically, adopted a concurrent engineering approach and operated in an environment of open communication and knowledge-sharing. A key enabler was an agreement between the prime and the participating suppliers that the prime would not compete with the suppliers 'until lot x.'

One of the key participating suppliers was chosen for its particular expertise in machining and welding. When the team began to search for new solutions to the weld cracking problem, this particular supplier began discussing the welding problem with a tool supplier with which it had developed a long-term relationship. The key supplier and the subtier tool supplier were in fact located right next to each other and had worked together for many years. Together, they had accumulated extensive prior experience with riveting processes in other projects and they explored riveting as an alternative to welding for the high temperature application. They soon converged on a promising approach to fastening the high temperature components by riveting. The riveting idea, originating from the key supplier and its tool supplier, was brought forward to the prime contractor and an integrated product team was organized to include the prime, the key supplier and the subtier tool supplier.

Riveting showed promise for eliminating the welds and their associated cracking problem, and also appeared to allow much simpler and less expensive manufacturing processes. However, such a major change in fabrication methods would require considerable redesign of individual parts and development of new manufacturing processes. Also, the tool supplier's experience base did not include the type of high temperature environment required for this application. A series of interrelated technical changes were sent into motion by the adoption of riveting as the preferred method for joining the various components. The new joining method required changes in how the components were linked together, involving a unique riveting sequence, due to changed interfaces and alignments. These changes caused redesign at the part detail level, requiring changes in the fabrication processes and in heat treatment sequences as well. Further, these changes paved the way for virtually toolless assembly of the final subsystem, which proved to be a very important outcome. In retrospect, cycle time reduction was not nearly as important as acceptable subsystem performance and cost savings. Also, meeting the exacting subsystem performance requirements resulted in important technological improvements in such areas as bonding, forming, casting, riveting, coating and cooling technologies, as well as in alloy metallurgy and manufacturing processes.

The case study identified major benefits derived from the resulting architectural innovation in designing, manufacturing and assembling the subsystem. Riveting significantly reduced the risk associated with fabrication by eliminating welding and the associated cracking problem. More than a five-fold cost reduction was achieved in developing this new generation subsystem, compared with the cost of the last prototype unit developed during the previous phase of the programme, along with a significantly increased manufacturing yield. The prime contractor was able to avoid significant capital investment by depending upon equipment already in place at supplier facilities. The prime was also able to retain technical control of the final assembled product by employing a proprietary coding technology. The key supplier, as well as its tool supplier, became effective members of the team, assured of longer-term business. Also, the tool supplier, enhancing its core competence through its participation in the project, was able to transfer newly gained high tolerance machining expertise to its automotive business, giving it a significant technical advantage over its competitors.

4. Conclusions

Perhaps the most important result derived from the research is that there exists an important opportunity for realizing significant benefits by proactively integrating key suppliers, and possibly lower-tier suppliers as well, early in the concept exploration and definition stages of product development. These benefits result from innovations in the system architecture that are enabled by suppliers. Furthermore, the research suggests an extension of the concept of architectural innovation to include changes not only in product architecture but also in the interfaces between the various product elements for which the suppliers are responsible, wherein each participating member provides those portions of the product and those specialized technical skills for which they are best suited.

In addition to the establishment of integrated product teams, long-term commitment to suppliers, collocation, joint responsibility for design and configuration control, seamless information flow, and retaining flexibility in defining system configuration stand out as key enablers. Important contributing factors include supplier-capability-enhancing investments, target costing, and incentive mechanisms that make such cooperative behaviour possible (e.g., not-to-compete agreements between the prime and the suppliers, long-term warranties, agreements to protect trade secrets), along with relief from military specifications and government oversight requirements. Recent acquisition reform initiatives replacing military specifications with performance-based commercial or nongovernmental standards and practices should help foster the types of enablers and practices our research has identified. Moreover, at a deeper level, our research underscores the importance of active government championship, not merely tolerance, of such closely-knit customer-supplier relationships necessary for the type of innovative outcomes reported here.

This research suggests that current approaches to the creation of long-term partnerships or strategic alliances with suppliers, focusing on new product or technology development, could benefit from the lessons learned from these two case studies. Namely, under well-defined circumstances, the specific conditions most conducive to architectural innovation can be more proactively created and nurtured. For example, in many instances where the key knowledge base resides with suppliers, architectural innovation will be hampered if suppliers are not brought on board as full participants in the very early stages of product development. Long-term relationships with suppliers can be created with architectural innovation as a primary and explicit goal in product development.

These initial findings also have a number of broad implications. Chief among these is the recommendation that technology supply-chains be designed and managed pro-actively. To do this, 'make-buy' strategies can be based on a stronger understanding of specialized technological capabilities across the supplier network and on a cumulative definition of the core competency of the entire value chain, most particularly over the supplier network. A corollary idea is that firms can build enduring competitive strength by leveraging the specialized knowledge bases resident over their supplier networks, through mutually beneficial arrangements and incentive mechanisms.

A cautionary note should also be appended to these initial findings. If the inter-organizational relationships, practices, processes and enablers were replicated in similar experiments, involving other products or systems, it is by no means certain that the types of benefits identified in the paper will always be realized. The reported outcomes were not foreseen at the outset of the project; in both cases the beneficial results may well have come as a surprise to the participants. This is possible even though they were clearly motivated to break with the past and to try new ways of designing and developing complex military systems.

Architectural innovation can certainly take place in a single-firm product development environment, without supplier participation. Nevertheless, it is clear that the examples of architectural innovation summarized above would not have taken place without early supplier participation in product development. Significant benefits were derived from the arrangements. Further research, both on-going and planned, seeks to identify the types of products or systems which offer the greatest opportunity for architectural innovation and where significant benefits can be gained. It also strives to define more precisely the conditions under which architectural innovation can be achieved.

Acknowledgements

The financial support made available for this research by the Lean Aerospace Initiative at the Massachusetts Institute of Technology is gratefully acknowledged. All facts, opinions and conclusions expressed herein are solely those of the authors and do not in any way reflect those of the Lean Aerospace Initiative, the sponsoring agencies or organizations or MIT. The latter are absolved from any remaining errors or shortcoming for which the authors take full responsibility.

References

Brown, S.L. and Eisenhardt, K. (1995) Product development: past research, present findings, and future directions. *Academy of Management Review*, **20** (2), April, 343–378.

Clark, K.B. (1989) Project scope and project performance: the effect of parts strategy and supplier involvement on product development. *Management Science*, **35** (10), October, 1247–1263.

Clark, K.B. and Fujimoto, T. (1989) Lead time in automobile product development explaining the Japanese advantage. *Journal of Engineering and Technology Management*, **6**, 25–58.

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

Cusumano, M.A. and Takeishi, A. (1991) Supplier relations and management: a survey of Japanese, Japanese-transplant, and US auto plants. *Strategic Management Journal*, **12**, 563–588.

Dyer, J.H. (1996) Improving performance by transforming arms-length relationships to supplier partnerships: the Chrysler case. Draft Unpublished Paper, The Wharton School, University of Pennsylvania, February 1, 43 pp.

Dyer, J. H. and Ouchi, W.G. (1993) Japanese style partnerships: giving companies a competitive edge. *Sloan Management Review*, **35** (1), Fall, 51–63.

Eisenhardt, K. (1989) Agency theory: an assessment and review. *Academy of Management Review*, **14**, 57–74.

Fine, C., Gilboy, G. and Parker, G.G. (1995) Technology supply chains: an introductory essay. Draft Unpublished Paper, MIT Sloan School of Management, Presented at the International Motor Vehicle Program (IMVP) Annual Sponsors Meeting, Toronto, May.

Gerlach, M. (1992) The Japanese corporate network: a blockmodel analysis. *Administrative Science Quarterly*, **37**, 105–139.

Grabher, G. (ed.) (1993) *The Embedded Firm: On the*

Socioeconomics of Industrial Networks. London: Routledge.

Gulati, R. (1996) Social structure and alliance formation patterns: a longitudinal analysis. *Administrative Science Quarterly*, **40**, 619–652.

Gulati, R., Khanna, T. and Nohria, N. (1994) Unilateral commitments and the importance of process in alliances. *Sloan Management Review*, Spring, 61–69.

Henderson, R.M. and Clark, K.B. (1990) Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, **35**, 9–30.

Hoult, D.P. (1997) Product Development with Suppliers – The Role of Database Commonality. *Society of Automotive Engineers (SAE), Technical Paper Series*, #970776, SP-1266, 7 pp.

Jarillo, J.C. (1988) On strategic networks. *Strategic Management Journal*, **9**, 31–41.

Kamath, R. and Liker, J.K. (1994) A second look at Japanese product development. *Harvard Business Review*. November–December, 154–160.

Liker, J.K, Kamath, R.R., Wasti, S.N. and Nagamachi, M. (1996) Supplier involvement in automotive component design: are there really large US/Japan differences? *Research Policy*, **25**, 59–89.

Lucas, M.V. (1996) Supplier Management Practices of the Joint Direct Attack Munition Program. Master's Thesis for a Joint Degree, Department of Aeronautics and Astronautics, and Technology and Policy Program, Massachusetts Institute of Technology, June.

Masten, S.E. (1984) The organization of production: evidence from the aerospace industry. *Journal of Law and Economics*, **27**, 402–417.

Nishiguchi, T. (1994) *Strategic Industrial Sourcing: The Japanese Advantage*. New York: Oxford University Press.

Powell, W.W., Koput, K.W. and Smith-Doerr, L. (1996) Interorganizational collaboration and the locus of innovation: networks of learning in biotechnology. *Administrative Science Quarterly*, **41**, 116–145.

Provan, K.G. (1993) Embeddedness, interdependence, and opportunism in organizational supplier-buyer networks. *Journal of Management*, **19** (4), 841–856.

Stiglitz, J.E. (1989) Principal and agent. In Eatwell, J., Milgate, M. and Newman, P. (eds.), *Allocation, Information, and Markets*, New York: W.W. Norton & Co., Inc.

Thorelli, H.B. (1986) Networks: between markets and hierarchies. *Strategic Management Journal*, **7**, 37–51.

Tirole, J. (1990) *The Theory of Industrial Organization*. Cambridge, MA: The MIT Press.

Ulrich, K. (1995) The role of product architecture in the manufacturing firm. *Research Policy*, **24**, 419–440.

Virag, D. and Stoller, N. (1996) Doing More for Less: Gaining Design and Cost Efficiency Through 'Integrated Supply Based Management.' *Society of Automotive Engineers (SAE), Technical Paper Series*, #960542, February 26–29, 37–41.

von Hippel, E. (1988) *The Sources of Innovation*, New York: Oxford University Press.

Ward, A., Liker, J.K., Cristiano, J.J. and Sobek, D.K. III (1995) The second Toyota paradox: how delaying decisions can make better cars faster. *Sloan Management Review*, Spring, 43–61.

Williamson, O.E. (1975) *Markets and Hierarchies*. New York: Free Press.

Williamson, O.E. (1989) Transaction cost economics. In Schmalensee, R. and Willig, R. (eds.), *Handbook of Industrial Organization*, Amsterdam: North-Holland, 136–182.

Womack, J.P., Jones, D.T. and Roos, D. (1990) *The Machine that Changed the World*, New York: Maxwell MacMillan International.

Notes

1. Lean Aerospace Initiative (LAI) is a research programme at MIT, jointly sponsored by a group of major aerospace companies and government agencies led by the US Air Force, aimed at bringing about fundamental performance improvements in the defence aerospace industry, as well as in government operations, leading to greater affordability, higher productivity, improved quality, and enhanced technological competitiveness. The research reported in this paper is based on on-going joint research by the Supplier Relations and Product Development research teams.
2. For a more comprehensive discussion, see Grabher (1993).
3. Refer to Womack et al. (1990) for an early and definitive exposition of lean production principles and practices.
4. These results are due to Kamath and Liker.
5. These results are due to Liker et al., p. 86.
6. For a detailed discussion focusing on Chrysler, see Dyer (1996).
7. That is, prior to Milestone 1 (i.e., during the requirements definition and concept exploration and definition phases).
8. These and the earlier survey findings just reported are due to Kirkor Bozdogan, 'Supplier Integration into Design and Development: The Drive for Architectural Innovation,' Presentation before the Lean Aerospace Initiative Executive Board (November 13, 1996), Dayton, Ohio.
9. This discussion draws on the unpublished Master's thesis by Malee Lucas (June 1996).