Acquisition Strategies For Commonality Across Complex Aerospace Systems-of-Systems

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Commonality is a system architecting strategy widely used to improve affordability and reliability of families of products. However not all commonality is beneficial, and organizations must balance commonality benefits and commonality costs to pursue a successful strategy.

The existing literature on commonality assumes that all commonality decisions are made within a single organization. This is not the case for NASA's human exploration architectures which are acquired through a network of prime contractors and sub-contractors. This thesis examines how the acquisition strategies chosen for NASA's human exploration architectures affect the realization of commonality in those architectures, and suggests ways in which acquisition architectures can be planned to improve commonality outcomes.

The thesis synthesizes the requirements of NASA's exploration architectures and commonality best practice from existing literature. It also examines the Federal Acquisition Regulations in detail to assess the limitations on government acquisition structures in the United States, and postulates a range of acquisition structures open to NASA.

New research data is presented which specifically targets the interplay between acquisition and commonality. An assessment of practitioners' views on acquisition strategies for commonality examines three detailed case studies as well as summarizing a broad range of shorter interviews across NASA and DOD projects.

Each of the postulated acquisition structures is evaluated against the NASA acquisition requirements and the synthesized commonality best practice.

The evaluation demonstrates that current NASA acquisition strategies are geared towards commonality through reuse of existing components and systems, and forward-thinking investment in future commonality opportunities is unlikely. New strategies which involve less emphasis on competition between contractors in favor of greater continuity with experienced contractors are recommended to improve commonality. However, the commonality advantages from such strategies may be offset in a wider perspective by the costs of using such non-competitive acquisition structures.

Thesis Supervisor: Edward F. Crawley
Title: Ford Professor of Engineering

For Alexandra

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True to type for a system engineer though it may be, I thought I could neatly divide the people I must thank for this thesis into three categories: those without whom this thesis would not have been possible, others without whom the thesis would have been much poorer, and still others who made the work of producing it a far lighter burden than it would otherwise have been. That proved an impossible task, as in retrospect so many contributions were critical, and made with more effort, good grace and dedication than I could ever reasonably expect.

Professor Ed Crawley, for example, falls into all three categories. Into the first category, for taking a chance on a lawyer in his Space Systems Architecting Group and for guiding me through the selection of case studies and other pitfalls for the unwary new graduate student. Ed falls too into the second category, with his unstinting insistence on excellence, his unwillingness to let the limitation of twenty-four hours per day hold him back in any way, and his generosity in constantly involving me in fascinating work in both Cambridge and Washington DC which fell outside the narrow scope of my thesis. And after many weekends of Vermont skiing and Friday evening drinks, Ed cannot help but fall firmly into the third category also. Thank you, and I hope we work together long into the future.

My family, who also span all three categories, through thirty years of encouragement, love, laughter and friendship, know how much they mean to me, and I set down here their endless contribution more so that others might know it also. Likewise my fiancée, Alexandra, to whom this thesis is dedicated for her endless patience and good humor through the best and the hardest times. No simple acknowledgement can do justice to your contribution.

The thesis would not have been possible without the generosity of time and effort by all of the participants in the case studies and the scoping interviews. You know who you are, and although the terms on which most of you agreed to speak with me prevent me thanking you individually, know that the conclusions of this thesis reflect your collective effort.

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Thank you also to Ryan Boas, Wilfried Hofstetter, Richard Rhodes and Bruce Cameron for their scholarship, intelligence and insight, shining light into the dark corners of commonality and setting the foundations on which much of this thesis is based.

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To all of you I have met during my two years in the United States, thank you for making me so welcome, for teaching me about hockey and football, and for listening for hours as I tried to explain cricket. It was a pleasure to meet you, to work with you and to learn from you. Thanks to modern technology I know that we will continue to do so for many years to come, wherever in the world we are. In that respect, the conclusion of this thesis marks, to paraphrase Churchill, not the end, nor the beginning of the end, but, perhaps, the end of the beginning.

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CHAPTER 1: INTRODUCTION AND OVERVIEW

1.1 MOTIVATION

Commonality is a system architecting strategy widely used to improve affordability and reliability of families of products. However, not all commonality is beneficial and injudicious use of the strategy can actually increase cost and risk. Thus commonality becomes a balancing act between cost and benefit.

Such a balance has been achieved in many industries, among them familiar examples including cars, aircraft and power tools, where a single corporation is in sole charge of producing a product. The balancing act becomes more difficult as the number of organizations involved grows and as a system becomes more complex. NASA oversees highly complex product developments which involve many contractors, research organizations and government teams. Often the end goals are tied to shifting political positions which move faster than systems to achieve the goals can be built.

The difficulty of successful implementation in the space sector is perhaps only matched by the potential benefits of commonality. Commonality reduces the number of development projects in a space architecture, and the consequent capital cost and technical risk. Recurring costs likewise reduce with commonality because fewer people are required to maintain the smaller number of systems, and economies of scale and faster learning make manufacture cheaper. Additionally, the uniquely high logistics and sparing costs involved in operating space projects like the International Space Station mean that the cost savings of commonality during the operating phase can be significant.

Previous studies of commonality have identified a range of tools for achieving a near optimum level of commonality. Most of these studies have assumed that the developing organization has total control over the product development process. In contrast, for the human spaceflight architecture, NASA controls the development process through a network of contracts, with a necessarily imperfect system of incentives and communication. This system of indirect implementation led the 2009 Augustine Committee to find that *"in many instances, one of the more significant discriminators in development and operations costs is neither what NASA procures nor who supplies it – but rather how NASA procures and operates a system" (Augustine et al, 2009).*

1.2 GENERAL OBJECTIVE

Motivated by the potential but unrealized benefits of commonality, this thesis examines better commonality could be achieved across NASA's human spaceflight architecture by considering commonality impacts when planning architecture acquisition.

This work is not intended to suggest that work should not be split between contractors in large, complex, expensive endeavors like human spaceflight architectures – in fact such a split is both practical and inevitable. Instead, this study examines the acquisition tools that will allow commonality opportunities to be realized even when they occur across the systems of multiple contractors.

1.3 BACKGROUND PRACTICE

Literature Review

In analyzing how acquisition methods affect the realization of commonality in complex architectures, this thesis draws on three areas of literature. The first is the field of architecting for commonality. From this body of work are drawn the processes, techniques, benefits and penalties of designing architectures with commonality. The second is the literature on government contracting. This field describes the permissions and limitations of government organizations' acquisition processes, and the factors that lead to successful contracting. The final field concerns the acquisition characteristics of space systems and the space industry. The products which the space industry requires are unique in terms of acquisition characteristics.

This thesis draws together the three fields as shown in Figure 1. At the center point of the three fields lies a successful commonality acquisition strategy for NASA.

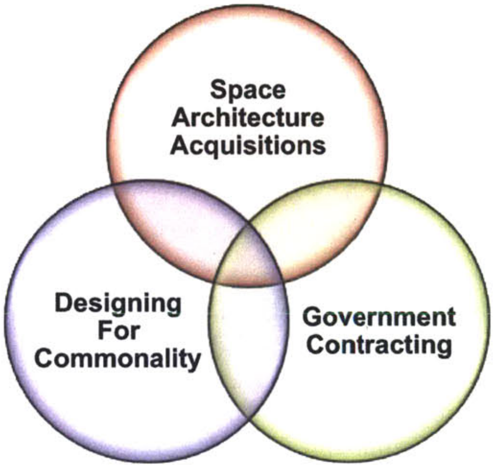

Figure 1: Areas of literature review

The two works which are most closely connected to this analysis are Rhodes' study of the management of commonality in NASA (Rhodes, 2010), and Scherer's detailed review of economic incentives in government contracting (Scherer, 1964).

Rhodes offers detailed guidance on managing commonality, and draws on several case studies both within NASA and outside of NASA. His conclusions are covered in more detail in section 2.2. Rhodes focuses on projects where the commonality was between products under the direct control of a single project office, for example between two variants of a space suit. As such, Rhodes is an important starting point for this thesis which expands the management lessons of Rhodes to address the situation where the potential variants are being developed by different organizations.

Scherer's work does not focus on commonality. Instead, it examines the raw metrics of acquisition success: cost, schedule and performance. Scherer does look in detail at how economic incentives in defense contracting can be used to improve project success. Broadly, he concludes that the effectiveness of direct contract incentives is often overstated, and wider market forces play a role in the way in which contractors deliver projects. Scherer bases his conclusions on a quantitative study of the acquisition of complex systems including missiles and aircraft, and a qualitative analysis of the economic incentives which drive successful acquisitions. As the starting point for much of the analysis of contractor behavior in this thesis, Scherer's work is discussed in more detail in Chapter 2.3.

Designing for commonality

The theory of designing for commonality has developed a rich selection of academic work. Ulrich & Eppinger (2000) discuss commonality in the market-driven terms of platform planning, commonality and differentiation. The place of commonality alongside other architecting strategies was analyzed in the overview paper by Crawley et al. (2004). Recognizing that terminology differs significantly between the different commonality applications, the RAND Corporation produced a report suggesting a "commonality lexicon" (Held, Lewis, & Newsome, 2007). These theoretical overviews overlay a large number of more focused studies. In his 2010 thesis, Rhodes suggests distinguishing between the technical identification of commonality, the economic evaluation of technically feasible commonality opportunities, and the implementation of those opportunities which are both technically feasible and economically beneficial. This distinction is used to partition the focused academic writing on commonality.

The largest selection of commonality-focused literature concerns the technical identification of commonality. Generally, the technical methods involve functional decomposition of the concept, and cost comparisons of the final architectures when the formal embodiment of the function is common across variants (Gonzalez-Zugasti, Otto, & Baker, 2000), (Dahmus, Gonzalez-Zugasti, & Otto, 2001), (Stone, Wood, & Crawford, 2000), (Robertson & Ulrich, 1998), (Simpson, Maier, & Mistree, 2001). Hofstetter (2009) presented an architecting strategy specifically designed to deal with systems where the formal embodiment of function cannot be fully specified before the commonality decision needs to be made.

The evaluation of commonality opportunities covers both the development of a cost model for commonality and the analysis of competing alternatives once armed with the cost information. The literature in this area is scarce. Rhodes (2010) presents a detailed commonality cost model which builds on the work of Boas. Thevenot & Simpson (2004) present metrics for measuring the amount of commonality in a product family. One method of comparing competing alternatives developed in the literature is the use of "real options". Gonzalez-Zugasti, Otto, & Whitcomb (2007) applied options thinking to commonality. Rhodes (2010) demonstrated the real options system as applied to commonality in architecting space hardware.

The third aspect of architecting commonality, managerial implementation, is rarely addressed in the literature. There is less work on the implementation of commonality once technical opportunities have been identified. In his doctoral dissertation, Boas presents heuristics to manage two aspects of commonality, specifically time offsets between variants and divergence, a term which he used to describe the movement away from common design over time (Boas, 2008).

Despite the depth of academic research, commonality is not explicitly treated in handbooks on systems engineering. Neither the INCOSE Systems Engineering Handbook or the NASA Systems Engineering Handbook mention planning for commonality specifically, although the latter discusses the reuse of heritage products (INCOSE Technical Board, 2004), (NASA, 2007a).

In addition to those papers which focus on the architecting of commonality generally, many papers describe the application of commonality methods to specific engineering problems. Generally, the authors concern themselves with the identification of technical commonality opportunities in their given systems. This thesis focuses on commonality in complex space systems, an area in which there has been extensive technical analysis of commonality. For example, many papers on technical commonality were written during the architecting phase of what is now the International Space Station (Butler, 1987), (Fedor, Baune, & Waiss, 1986), (Gould, Heck, & Mazanek, 1991), (Boeing Aerospace, n.d.), (Tremblay & Crites, 1988), (Wensley, 1984), (Krauthamer, Gangal, & Das, 1990). Rhodes (2010) studied the implementation of commonality through three NASA cases. Ground system commonality for space architectures has been considered by Quinn (2008), Gilbert & van Leeuwen, (2003) and Nadel, (2007) among others. Architecture commonality at a higher level was considered in the development of space exploration architectures (Wooster, Hofstetter, & Crawley, 2005), (Hofstetter, de Weck, & Crawley, 2005), (Hofstetter, 2004), (Hofstetter, Nadir, Crawley, & Wooster, 2005). The architecture of the flexible path in the 2009 Augustine Report was based to a large extent on commonality between the elements required in architectures for travel to points in free space, small bodies like asteroids, the Moon and Mars (Augustine et al, 2009).

Space Architecture Acquisitions

The process of delivering large NASA projects has been the subject of several excellent books. The acquisition strategies proposed in this thesis were evaluated against a distillation of the processes and cultures presented in these books to ensure that the strategies did not require unrealistic organizational change.

Bromberg's book *"NASA and The Space Industry"* examines the relationship between NASA and it's circle of industry from the 1950s through to the 1990s (Bromberg, 1999). Of particular interest is that Bromberg identified the very commonality problem this thesis addresses in her research on the International Space Station. The following quotation summarizes the tension that underlies the acquisition of common systems:

> *"Political considerations dictated that as many centers as possible get a piece of the action. That would suggest that the station be divided into relatively independent pieces so that each of the participating centers could work up its part in relative autonomy. But [NASA Administrator] Beggs was promising a low-budget station, only $8bn in 1984 dollars, and one way to economize would be to standardize components common to all pieces and "mass produce" them. It would also be cheaper if some systems could be centralized...all this necessarily meant that the pieces doled out to the centers would be less independent. Each center would have to design its part of the hardware so that it would fit with the centralized systems and use standardized parts. Furthermore the job of designing the centralized systems would also have to be divided up among the centers. Whatever management team was put in place would have to deal with a complex distribution of tasks among the centers and a messy set of interfaces among the subsystems. " (p164)*

In retrospect, the management framework for the International Space Station was unsatisfactory. Bromberg documents a fragmented system where different centers developed their systems in relative autonomy, and the result was unsatisfying: *"It really took a toll to adjudicate the disputes that arose between the field centers...they were constant, they were difficult, they were sometimes vicious, and most of the time they were very parochial."* The question remained unanswered, even as International Space Station cost overruns strengthened the imperative to improve the affordability of complex space architectures.

In the same vein as Bromberg, but without her assessment of the difficulties of commonality, Levine offers an overarching view of the Apollo program in his work from the NASA history collection "Managing NASA in the Apollo Era" (A. Levine, 1982). Similarly, Kelly and Mindell describe the acquisition of particular Apollo systems, the Lunar Module and the digital flight computers respectively, in detail (Kelly, 2001) (Mindell, 2008). McCurdy adopts a slightly different approach in documenting NASA culture by capturing first hand perspectives from

NASA personnel (McCurdy, 1993). McCurdy's paper "The cost of space flight" is also a valuable reference to the acquisition difficulties of space systems (McCurdy, 1992).

More recently, the characteristics of the systems NASA acquires, and the industrial-government relations which underpin those acquisitions, were well described by Szajnfarber and her colleagues. Szajnfarber's study of the dynamics of the space industry supported an investigation into innovation across the NASA enterprise, rather than commonality (Szajnfarber, Grindle, & Weigel, 2009) (Szajnfarber & Weigel, 2009).

Turning from historical and theoretical summaries to the practicalities of acquiring space systems, NASA has produced literature of its own on the contracting process for space system acquisition. Chapter 7.1 of the NASA System Engineering Handbook is titled "Engineering With Contracts" and examines techniques for splitting work between contractors and NASA. It explains how the steps outlined in "NASA System Engineering Processes and Requirements" (NPR 7123.1) should be undertaken if a contractor is involved. It summarizes the major risks that can occur with contracting out work, illustrating those risks with lessons learned by NASA in the past (NASA, 2007a).

There is little in the literature that deals with the nature of space acquisition outside the NASA context. Amesse et al (2001) examine subcontracting in the Quebec aerospace industry from the perspective of its effectiveness as a technology transfer tool. In doing so, they provide three reasons why prime contractors subcontract: economy (subcontracting because the subcontractor can perform the work more cheaply), specialization (subcontracting because the prime lacks the resources, e.g. labor, to perform the work) and supply (subcontracting because the prime lacks the technical capability to perform the work). In a rare example of quantifying the effect of acquisition structures Koelle, (2010) deals with the cost effects of using subcontractors on development projects in his work on estimating launch vehicle costs. The launch vehicle cost models presented by Koelle utilize an adjustment factor which depends on the project acquisition structure.

Government contracting

At the intersection of space acquisitions and government contracting there exist a few papers, largely driven by the needs of the defense community. The most relevant is Moon's thesis "Identifying Federal Contracting Policy Changes To Improve Government Acquisition of Commercial Space-Launch Capacity" which suggests that allowing contractors to perform their own analysis given government-specified mission needs would be the most efficient way to deliver launch capacity (Moon, 1992).

The broader literature on government contracting is collected between two extremes. At one end, highly theoretical economic literature attempts to assess the most efficient contract type for particular applications. Examples of this type of analysis are Salanie (2005) and Bower & Dertouzos (1994). These works have been not been used in this thesis for their detailed economic analysis. Rather, the types of contract chosen for economic modeling were checked to see if they presented any new alternatives. In addition, the observations on government contracting practice made by the authors when comparing the economic model results to the established practice were useful.

Scherer's excellent economic analysis of the Department of Defense's weapons acquisition process throughout the 1950s, is grounded in empirical research and escapes the necessarily simplifying assumptions of much of the theoretical economic literature. Scherer's analysis is so central to this thesis that his work is examined in more detail in section 2.3 as the various forms of contract are discussed.

At the other extreme are the practical guidebooks to government contracting produced for acquisition professionals, which are focused on the process of contracting with little analysis of how the process could be improved. For example, the Defense Acquisition Guidebook (Defense Acquisition University, 2011) provides "discretionary best practice" in the government management of defense programs . Much of the analysis in chapter 2.3 is grounded in this material. Rendon and Snider's book "Management of Defense Acquisition Projects" (Rendon & Snider, 2008) is a recent summary of acquisition management aimed at the practitioner .

Also at this practical extreme are the policy adjustments recommended by government advisors from time to time. The most significant participant in this exercise is the Government Accountability Office (GAO) and there is a vast body of work by the GAO on particular NASA projects, and government contracting strategies more generally. A particularly relevant article concerns "NASA Contract Management" (Government Accountability Office, 1993).

Between the two extremes sits a small body of academic literature that focuses on new contract types. Bertran & Vidal (2005) examine the success of Public-Private Contracting for the Galileo and Skynet satellite constellations. Hashimoto extends this analysis to include a more extensive analysis of space projects including elements of the human spaceflight architecture such as the Space Shuttle and the Kibo module (Hashimoto, 2009).

Most of the acquisition literature focuses on defense acquisition because its larger budget means larger potential gains from new methods. From the NASA perspective, periodic updates to the NASA acquisition community serve a similar function to the Defense Acquisition Guidebook (for example Dale (2008) and NASA (2007b)). These short memos outline best practice. No works similar to Rendon and Snider which focused on NASA were identified, which is unsurprising considering that the NASA acquisition task is only a fraction of that of the defense forces.

There are several works in the literature which address the problems of defense acquisition from other "ility" perspectives. The closest to commonality is probably interoperability, which has received much attention in the new "netcentric" vision for the US defense forces. The technical report by Meyers et al (2005) "Including Interoperability in the Acquisition Process" is a good example of this trend. An excellent example of design of acquisition structures for innovation is the work of Birkler et al (2000) in their monograph on new acquisition approaches for innovative systems within the DOD.

Gap Analysis

The conclusion of the literature review is that no previous work has answered the question of how to acquire space systems that support commonality. However, there are extensive bodies of work on the separate areas of commonality design, space acquisition, and government contracting. The best approach for NASA to acquire systems with smarter commonality lies at the intersection of these three fields.

1.4 SPECIFIC OBJECTIVE

The specific objective of this thesis is to develop a rigorous evaluation of a range of acquisition strategies for commonality benefit, and to conclude which strategies will best promote beneficial commonality. A cartoon depiction of this analysis is shown in Figure 2. The difficulty in analyzing the acquisition strategies was not so much a lack of acquisition options, as everyone interviewed in the course of this thesis had an opinion on the best way for NASA to acquire its space systems. Rather, the difficulty in this thesis was to present a traceable and transparent analysis which captured the hunches of all of the interviewees, synthesized with formal acquisition regulations and commonality best practice. To achieve this, the thesis develops a "stoplight" chart for each acquisition strategy. The stoplight chart evaluates the facets of each acquisition strategy and summarizes their effect on commonality as one of four categories: helpful (green), uncertain (yellow), unhelpful (red) or no effect (grey).

It must be said at the outset that creating acquisition strategies is not able to achieve the same certainties of design as the space systems thus acquired. Changes in the economy, the market for defense products and the decisions of industry executives and NASA managers all play a part in determining the effectiveness of an acquisition structure. Further, commonality is not the goal of a government acquisition structure; rather it is to obtain products at value for the government dollar. This means commonality may not be the best option in all instances. For example, there is an essential tension in designing an acquisition strategy between promoting cost savings through competition and cost savings through commonality. It is in part due to this uncertainty that this thesis attempts to adopt a very methodical structure to the development of the preferred acquisition strategies. Readers are invited to examine the assumptions which underlie each of the recommended acquisition strategies and make use of those aspects most applicable to the case at hand.

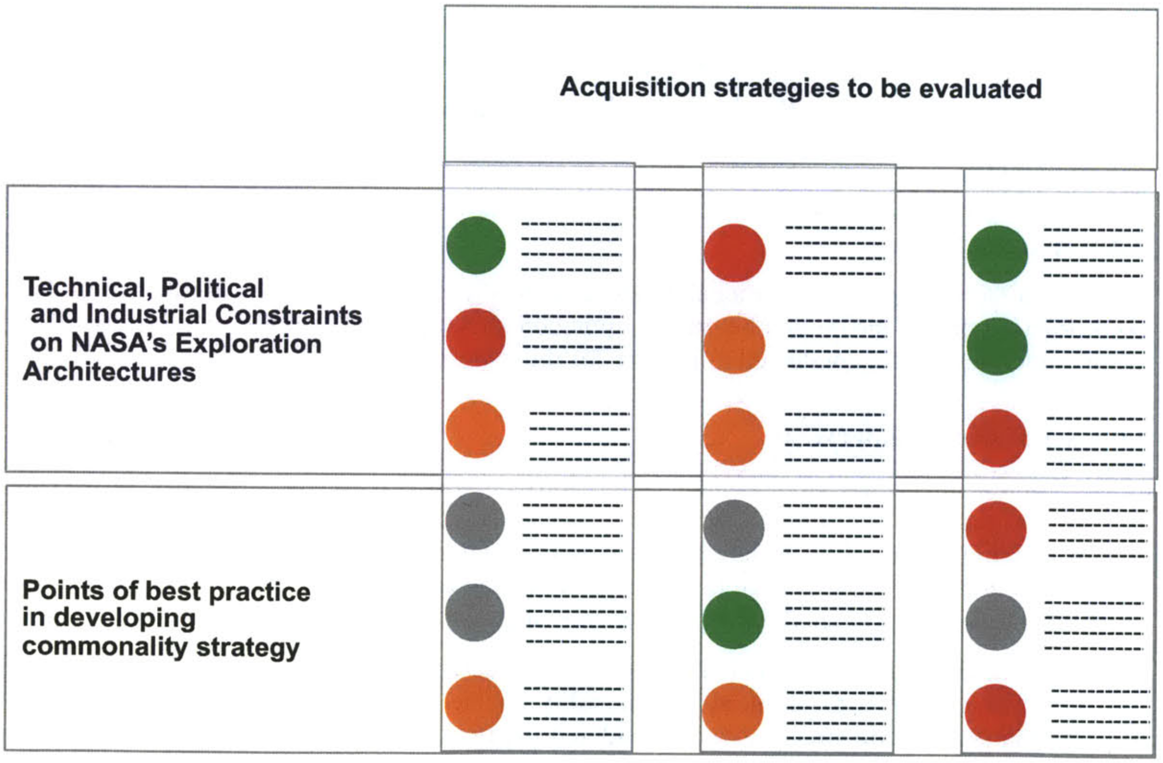

Figure 2: Cartoon depiction of acquisition strategy evaluation

1.5 METHODOLOGY

Why in-depth case studies were chosen

There are, broadly, two possible methods that could have been undertaken to analyze the interaction of commonality strategies with acquisition strategies. A study quantitatively examining many projects ("large-n") was rejected in favor of a small-n study which conducts qualitative, in-depth, case studies after initial scoping interviews (Yin, 2009).

A "large-n" study covering many NASA acquisitions involving commonality was rejected despite it having been successfully applied to contract structures by Scherer's analysis of Department of Defense contracts through the late 1950s and early 1960s for several reasons. First, significant difficulty was anticipated in gathering enough accurate data to support this approach. The commonality strategy and acquisition structure of a project are both difficult to gage by easily accessible metrics (Boas, 2008).

Second, with respect to measuring commonality performance, there is no external metric by which the benefit initially anticipated and finally realized commonality of the system can be judged. Commonality of itself is neither beneficial or detrimental, and changes in commonality could indicate either a sound commonality strategy adjusting to the level of commonality which gave maximum benefit, or a poor commonality strategy failing to control the amount of commonality between variants. There are also significant differences between organizations as to how to measure and cost commonality (Boas, 2008).

There are also difficulties in measuring the acquisition strategy of a program. No two acquisition strategies are exactly alike, though similar approaches could be binned together. The detailed acquisition structure of projects is infrequently reported in conference and journal papers and sometimes confidential. Additionally, the acquisition structure can change throughout the acquisition process as the in-vogue acquisition trends change.

A final, and very practical, difficulty with a large-n study within NASA projects was that at the time of this study the Constellation program was drawing to a close and there was significant organizational change within NASA. Major contracts were being terminated or under threat of termination, which meant that NASA acquisition executives rightly had more pressing concerns than helping gather data.

Therefore a large-n study of commonality was discarded in favor of a smaller number of in-depth cases, focused on the interaction between acquisition structures and commonality results. Initial scoping interviews were conducted to prepare for the in-depth cases.

Purposes of scoping interviews

Initial scoping interviews were conducted one-on-one with 17 system architects, project and system managers and acquisition experts who work on complex aerospace systems. Additionally, five presentations were given to larger groups with an interest in commonality. The interviews, which lasted between about half an hour and an hour, had four purposes. Appendix A contains a list of the interviews conducted during the scoping phase of this thesis.

First, the interviews asked whether the acquisition structure chosen to implement commonality had an effect on the realization of commonality in the developed system. The interviews indicated that acquisition structure was considered to affect commonality, which encouraged this thesis to proceed.

Second, the interviews collected shallow data across a range of projects. Most often, the data collected was a cloud of conclusions and residual learning gathered from past commonality experiences. The data sacrificed for breadth of study was the background to developing those conclusions. Therefore it was not possible to assess the reasons for the beliefs that the interviewees held in the shallow study, but it was possible to assess the final viewpoint they reached. This data served as a useful comparator with the conclusions of the in-depth case study results.

Third, the interviews identified the areas of interest to the interviewees in the management and acquisition of commonality. These areas were considered as points of focus when constructing the semi-structured interviews for the in-depth case studies.

Fourth, the interviewees suggested possible case studies which could be examined in more depth. The conditions of confidentiality under which two of the case studies in this thesis were undertaken mean that it is not possible to state whether any of the scoping interviewees took part in the broader case studies.

The process of conducting the scoping interviews took approximately 12 months. There was some overlap between the commencement of the in-depth case studies and the conclusion of the scoping interviews.

Summary of the in-depth case studies

In-depth case studies were chosen as the method to assess the effect of acquisition structures on commonality. Three in-depth case studies were chosen.

The criteria for a potential case becoming a case study were:

- A family of end-products with common elements was acquired
- The end-products had similar technical difficulty to projects likely to be included in NASA's human spaceflight architecture;
- Multiple corporations and / or government organizations were involved in developing the family of end-products
- Accessibility to a range of people involved in the development of the family, ideally including project managers, system engineers and project executives.

In addition to these mandatory criteria, a series of other comparisons were drawn between the potential case study and likely elements of NASA's human spaceflight architecture. Table 1 shows a summary of these comparisons. The more similar comparisons, the more likely any findings from the case would be applicable to NASA's human spaceflight architectures. It was not desirable to have a complete match in all categories, however, because the likelihood of finding different approaches to those currently used by NASA increases as the case studies move further from being directly connected with NASA.

Conduct of the in-depth case studies

The case studies were generally conducted at the offices of the organization being investigated. Prior to visiting the site, a point of contact was established who developed a pre-planned schedule of interviews with personnel across the organization. Each interview lasted about an hour. Follow-up telephone calls were arranged after the site visit.

Interviews were not recorded, but handwritten notes were taken during the interview process. The short-form notes were typed into more comprehensive recollections of the interview, usually within 24 hours.

Table 1: Relevance of Case Studies to NASA's Acquisitions

	CASE STUDY OF DOD RADIOS		CASE STUDY OF LAUNCH VEHICLES		
Comparison	**Similarity**	**Notes**	**CS2**	**CS3**	**Notes**
Purpose of Commonality	Medium	DOD looks for interoperability, then affordability. NASA primarily looks for affordability.	Medium	Medium	CS2 looks for reliability. CS3 looks for flexibility.
Unit cost	Low	JTRS unit cost = $3,000 to $200,000 NASA unit cost = Order $100 million	Medium	Medium	Unit cost of order $10 million
Number of units	Low	JTRS proposes acquisition of ~250,000 radios NASA will acquire high-value exploration architecture elements in order 10s.	Medium	Medium	Launch rates of approximately 10 per year
Program cost	High	JTRS development cost estimated at ~$5bn, total program cost ~$37bn NASA development budget for, eg Orion, ~$5-10bn, then about $1bn / flight on acquisition.	High	High	Development costs are unknown, but similar hardware indicates likely similar cost
Technological Complexity	High	JTRS is an integrated hardware and software system incorporating significant R&D. 1.6m lines of code in the most advanced waveform.	High	High	Development costs are similar.
Acquisition environment	High	Both are government acquisition projects	Medium	Medium	CS2 and CS3 are commercial projects.
Development purpose	Low	The objectives of each organization (Warfighting and Space Exploration) are different.	Medium	Medium	CS2 and CS3 most focused on LEO / GEO
Organizational structure	Medium	DOD has separate services which operate different platforms in support of a common mission. NASA has separate program offices which develop different platforms in support of a common mission.	Low	Low	CS2 and CS3 are much smaller than NASA
Issues with implementation of commonality	High	Need to include commonality with heritage systems Lack of centralized funding for common development Variants are offset in development Policy changes disrupt development plans Plans executed on yearly budgets Planning for future technology developments	Medium	Medium	CS2 and CS3 do not have fixed yearly budgets, but do experience the other difficulties described at left.
Number and type of contractors	High	The number of subcontractors able to build the software and hardware for the radios is small. The number involved in NASA programs is likely smaller, but not by much. Some of the same organizations are involved in both.	Medium	Medium	Systems engineering done in-house by CS2 and CS3. More streamlined supply chains in CS2 and CS3 than in NASA.

1.6 OUTLINE

As stated in section 1.4, this thesis aims to produce a rigorous and transparent stoplight chart comparing acquisition strategies. The structure of the remainder of this thesis is therefore best conceptualized by Figure 3 which shows how each chapter contributes to producing the stoplight chart.

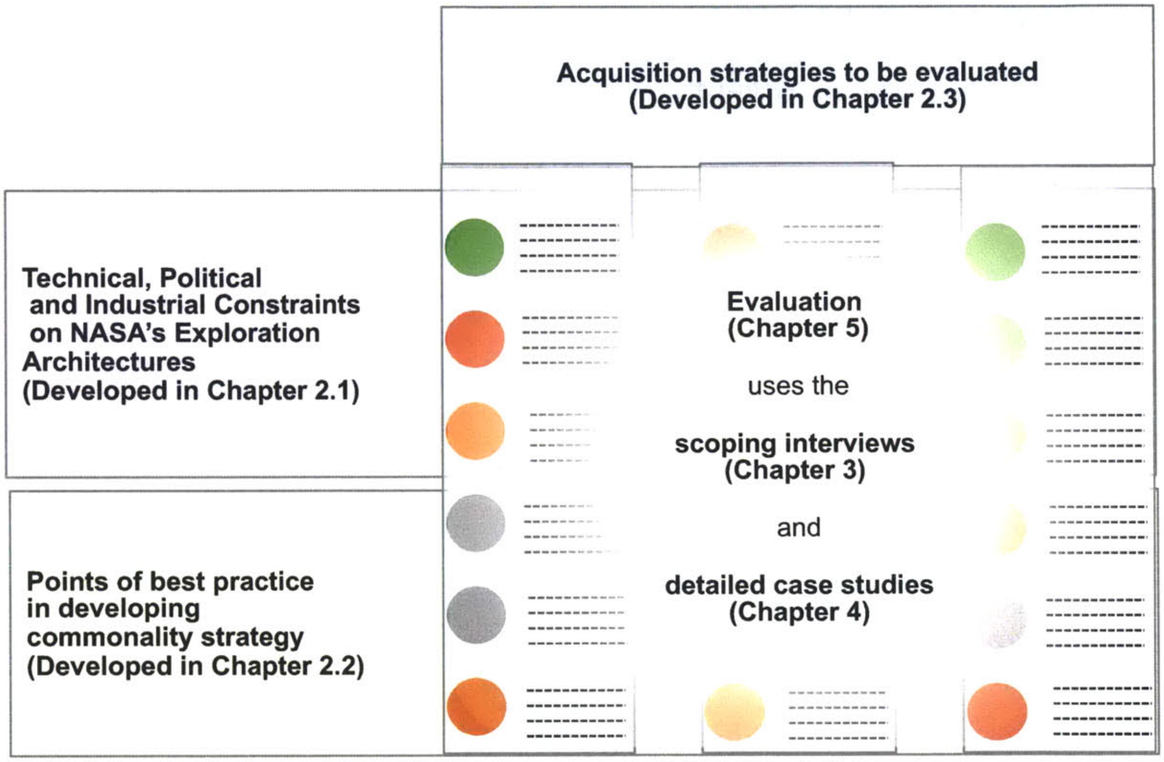

Figure 3: Each Chapter contributes to the Chapter 5 stoplight chart

Chapter 2 undertakes a synthesis of existing literature with observations made during the interviews to determine three questions. One, what are the essential features of NASA's acquisitions, especially those which distinguish a NASA program from other government or industry programs? This research draws mostly on historical accounts of NASA programs and culture. Two, what is the best practice strategy for commonality? This research summarizes previous work on commonality practice and theory and develops process maps to more precisely measure commonality performance. Three, what tools are available to the acquisition strategist in crafting an acquisition strategy? This section analyzes the Federal Acquisition Regulations, NASA policy documents and Department of Defense research.

Chapter 3 presents the results of the scoping interviews with a range of practitioners. It layers over the theoretical analysis of Chapter 2 an appreciation for the important issues in practice. The practitioners' views are used to answer six questions:

1. Have any acquisition strategies been used by NASA or DOD which focus on commonality?
2. Which acquisition strategies – actual or potential – could affect the amount of realized commonality?

3. To what extent do US Federal Government acquisition regulation and practices limit the acquisition strategies available for commonality?
4. What types of NASA projects would most benefit from an acquisition strategy focused on commonality?
5. What factors drive commonality success?
6. What are the obstacles to successful implementation of inter-contractor commonality?

Chapter 4 presents a search for better approaches through detailed case studies. Three detailed case studies are presented, one on acquiring a family of software defined radios and two on acquiring families of launch vehicles.

Chapter 5 then takes the acquisition strategies suggested by the literature and the case studies and assesses how they perform against the best practice for commonality and the constraints of NASA's acquisition needs.

Chapter 6 recommends acquisition strategies for NASA based on the analysis in Chapter 5.

NOTE ON TERMINOLOGY

Both the tasks of reading and of writing this thesis are helped considerably by agreeing to standard terminology at the outset. Standard terminology helps make sense of discussions about architecting, acquisition and commonality, all of which have particular concepts which become confusing quickly without agreement on what to call them. The following definitions are used throughout this thesis:

Engineering Aggregations

Program: A program is the highest level development effort, for example the Apollo program or the Constellation program. It contains several projects which work in concert to produce the program outcomes.

Project: A project is a development effort aimed at producing a product or a family of products, for example, the Saturn launch vehicle project or the Altair lunar lander project.

System: A system refers to any aggregation of hardware and software that produces a functional output, and is at a more detailed level than a project and a less detailed level than a component. For example, a life support system.

Component: A component is used to refer to the smallest useful parts of systems, for example bolts or flight computers.

Element: An element is a term used in this thesis when a statement made could apply equally well to systems or components.

Commonality

Family: A family is a collection of projects or elements with commonality. A family comprises a set of **variants,** each of which have some unique features which distinguish them from other family members.

Platform: The platform refers to the elements which are common across a family.

Acquisition Structures

System Integrator: The system integrator is responsible for system engineering at the program level. The system integrator may be NASA or a corporation under contract to assist NASA.

Prime Contractor: A prime contractor is responsible for a project. Usually a prime contractor reports to the government, but if a sole prime structure is used the prime contractor may report to that company.

Sole Prime: The term "sole prime" is used to describe a contractor responsible for an entire program.

Sub-Contractor: A contractor at a level below a prime contractor.

Contractor: Either an organization with a direct contract with NASA, or a generic term to describe any organization working on the architecture.

CHAPTER 2: SYNTHESIS OF NASA'S COMMONALITY ACQUISITION TASK

In the literature review of the previous chapter, it was demonstrated that no studies have examined how NASA's acquisition strategies can be used to improve commonality. Nevertheless, much can be synthesized simply based on the existing information. This chapter examines existing works on NASA culture, commonality best practice and government acquisition to synthesize the tradespace within which acquisition strategies must function. It is important to understand each of these aspects, because a commonality acquisition strategy must stand on all three pillars. A commonality acquisition strategy perfect for NASA will never be realized if it does not comply with government acquisition regulation. Structures which do not meet commonality best practice, or which fail to meet NASA's mission needs will be equally useless. We turn first to the acquisition characteristics which NASA's human spaceflight structures must meet.

2.1 ACQUISITION CHARACTERISTICS OF HUMAN SPACEFLIGHT ARCHITECTURES

The 1990 Augustine Report viewed NASA's mission as *"a difficult one, probably more difficult than that of any other organization in the world"* (Augustine et al, 1990, p. 18). It is likely the authors of the report were referring to more than just the technical objectives of the agency, for the industrial and political environment in which NASA's missions are undertaken make its achievement all the more impressive. The key technical, industrial and political facts of NASA's mission, together with their acquisition consequences, are summarized in Table 2. The table also notes two future possibilities which, if they occur, will change NASA's acquisition task.

The acquisition strategies which are likely to be successful for NASA must first take into account the unique technical difficulties involved in space hardware development. For example, the staggering complexity of all space systems precludes high level participation by small contractors, reducing the competitive pool for NASA's system integration tasks. Acquisition strategies must also take into account NASA's unique place in the fabric of United States industry and politics. For example, an acquisition strategy which did not spread contracts reasonably widely across the country would hamper a space program looking for broad Congressional support. Strategies which involve too much organizational change, disrupt the balance of industry, or require political support at Apollo-like levels are simply unrealistic. Therefore this section develops a set of acquisition "realities" for NASA.

A perfect acquisition strategy would meet all of these realities and still implement commonality efficiently across the architecture. However, as Chapter 5 shows, a perfect acquisition strategy has not yet been found, and some of the realities may need to give way to produce a more affordable and efficient space program.

At the outset, it is important to re-emphasize the types of products this thesis focuses on. NASA's acquisitions cover a broad range of products from IT services to supersonic aircraft prototypes to habitats for human spaceflight. In this thesis the focus is on products closest to the last category: components of the human spaceflight architecture. The realities discussed below apply only to this subset of NASA's acquisitions because it represents the only unique component of NASA's acquisition task.

In analyzing NASA through the eyes of its employees, McCurdy shows a changing organization. Its mission now is different to that which it fulfilled in the 1960s, and to some extent its culture has changed to reflect that evolution (McCurdy, 1993). It will continue to change, and so this section does not attempt to pin down exactly those features of the NASA of 2011, but rather to capture the fundamentals of NASA as written throughout its history. Generally, those fundamentals are likely to last the duration of the next human spaceflight architecture. However, two areas of possible future change – increased commercial activity and increased international cooperation – will significantly impact the exploration architecture if they occur. Therefore the potential acquisition strategies are also evaluated on their effectiveness should either or both of these possibilities become reality.

The conclusions in this section are based on histories of NASA and its projects, the opinions of interviewees (more fully documented in Chapters 3 and 4), and the author's own experience while preparing this thesis working with NASA and following its fortunes during a particularly revealing time in US spaceflight policy. Each of the correlations between fact and acquisition consequence could be examined in more detail to probe the strength of the connection.

Table 2: Summary of acquisition characteristics of any US Human Spaceflight Architectures

Technical Fact	**Acquisition Consequence**	
Space systems require research and development.	1	The acquisition strategy must fund research and development.
Space systems are highly complex.	2	The acquisition structure must be able to tolerate cost overruns and schedule slips which exceed initial estimates.
	3	The acquisition strategy must ensure its prime contractors can handle complex hardware-software systems costing hundreds of millions in development.
The historical development time for space systems is approximately a decade.	4	The acquisition strategy must be effective over development times of at least a decade.
	5	The acquisition strategy must deliver first flight within a decade.
NASA has extensive human spaceflight experience important for the success of future exploration missions.	6	The acquisition strategy must allow NASA to impart its human spaceflight experience to the contractor.
Complex spacecraft are prone to complex failures. NASA is held responsible for these failures.	7	The acquisition strategy must give NASA confidence in the reliability of its contractors design, manufacture and testing process.
Systems engineering and integration is performed best by those with experience in building the systems they integrate.	8	The system integrator(s) must have recent or ongoing engineering experience on human space systems.
Operation of space infrastructure is costly and has historically resulted in unsustainable architectures.	9	The acquisition strategy must achieve balance between up-front and recurring costs.
Industry Fact		
The US Government is the only customer for NASA's exploration architecture beyond LEO.	10	The acquisition strategy must not depend heavily on funding from non-government sources.
The production runs of the an exploration architecture are likely to be one or two of each element per year over a period of time that cannot be easily predicted.	11	The acquisition strategy must allow corporations to make a profit despite small production rates and uncertain production volumes.
Political Fact		
The ten NASA centers do not function as a cohesive unit.	12	The acquisition strategy must overcome inter-center parochialism.
Closure of any NASA centers will be politically difficult.	13	The Acquisition Strategy must allocate some work across all ten NASA centers.
Funding for NASA will vary over time.	14	The acquisition strategy must be robust to year-by-year changes in funding.
NASA will increase Congressional support if contracts are awarded across diverse geographical regions and contractors.	15	The acquisition strategy must allow work to be divided between the major aerospace contractors.
Future possibilities		
International cooperation on space exploration architectures may increase over future years.	16	The acquisition structure should allow international partners to fit into the acquisition program over time.
Commercial space companies may become increasingly capable and have customers other than the US government.	17	Acquisition strategies should utilize commercial space companies when the capabilities of those companies are proven.

Technical features of Human Spaceflight Architectures

The most obvious area in which acquiring space exploration architectures differs is in the technical characteristics of the acquired systems.

Technical Fact: Space systems require research and development.

The starting point in describing space exploration systems is that they often involve new technologies to go to new places and therefore their acquisition must fund some research and development. Space missions push the state-of-the-art and *"depend on some of the world's most advanced technology"* (Augustine et al, 1990, p. 5). As one of McCurdy's interviewees pointed out: *"if you want to make progress.. you've got to design things that have not been done before"* (p77).

Acquisition Consequence 1: The acquisition strategy must fund research and development.

The need for research and development influences the acquisition strategy, because the necessary research and development won't be done without funding. Research and development from exploration architectures can certainly benefit aerospace firms in bidding on additional contracts, but usually the case for future benefit alone is not strong enough to initiate the new ideas: *"contractors...tend to innovate in response to government requests"* (Szajnfarber, 2010).

By its nature, research and development is uncertain in its timeframe and cost. This means that funding strategies which depend too heavily on fixed-time, fixed-cost contracts will not be as effective in promoting research and development.

Technical Fact: Space systems are highly complex.

Even without new technology, space systems are very complex. There were *"six million components manufactured by thousands of separate contractors"* (Augustine et al, 1990, p. 5) on the Saturn V launch vehicle, and 2.5 million lines of software code on the Space Shuttle (Augustine et al, 1990, p. 5)[1]. Szjanfarber writes that *"Spacecraft embody significant "Product Complexity". Each subsystem is itself a complex system; many disciplines...are involved...and multiple different levels of maturity exist simultaneously in any given system"* (Szajnfarber, 2010). The complexities of space systems were brought to the fore early in the space program, when vibration on the early launch vehicles *"became one of the first so-called system issues – it transcended the realm of the structural engineer, the propulsion expert of the electrical engineer alone"* (S. Johnson, 2002, p. 9). Complexity leads to two consequences for acquisition.

Acquisition Consequence 2: The acquisition structure must be able to tolerate cost overruns and schedule slips which exceed initial estimates.

Both the need for new technology and the complexity of the space systems lead to cost overruns and schedule slips.

The 1990 Augustine Report pointed out how new technology makes it exceedingly difficult to propose accurate project costs, as *"uncertainties of yet to be demonstrated technologies alone preclude precision"* (Augustine et al, 1990, p. 18).

Complex space systems have *"a natural tendency...to grow in scope, complexity and cost"* (Augustine et al, 1990, p. 8) as the details of the initially uncertain system become more obvious, and the engineering detail needed to achieve the mission becomes clear. Additionally, the

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[1] (Herbella, 1992) quotes 7 million lines of code which need to be maintained across the entire shuttle program.

compounding effects of new technology, high performance demand, plus inevitable cost pressure lead to additional complexity as ingenious designers build more into their system: *"If you try to use all of the pig except the squeal"* philosophized one of McCurdy's interviewees, *"you're obviously making things work very efficiently. But...you end up with a more complicated system... failure in one thing cascades over into the other"* (McCurdy, 1993, p. 159).[2]

NASA's complex systems also entail complex failure analysis. Augustine points out that *"we should be prepared for the occasional failure"* (Augustine et al, 1990, p. 18), for failure is a key way in which learning progresses, particularly shown in the early years of the space program when *"experimentation more than theory determined the problems and solutions"* (S. Johnson, 2002, p. 8). The complex, costly and time consuming failure analysis such as that which followed the Apollo 1 fire is rarely factored into initial cost estimates, leading to increased difficulty meeting cost and schedule targets.

Finally, there is a very human reason for programmatic difficulties in NASA programs. NASA competes with other government programs for funding from Congress, and is at the disadvantage of not providing an essential service like power, housing, education or healthcare. NASA's planned work must be spectacular: *"unless expectations are sufficiently high, they won't attract interest and support, especially from governments"* (Rechtin, 1999, p. 101). Expectations are based on perceived value, which is benefit to stakeholders relative to the cost of the program. Therefore NASA programs are often established with great expectations and *"too little margin for the unexpected"* (Augustine et al, 1990).

Acquisition Consequence 3: The acquisition strategy must ensure its prime contractors can handle complex hardware-software systems costing hundreds of millions in development.

The responsibility for developing or integrating these complex systems often falls outside NASA, on "prime contractors". There are a limited number of companies with the technical expertise, management systems and financial capital to perform these projects. An illustration of the fragility of the top end of the industry is Bromberg's example of a 1997 $6 billion dollar contract on which *"Boeing declined to bid"*. Boeing's withdrawal meant that Lockheed Martin was the sole bidder (Bromberg, 1999, p. 177).

Table 3 shows the 2010 revenues of some of the key contractors which might be involved in the development of an exploration architecture. Importantly, not all of these corporations derive their revenue extensively from the space sector. The total revenues of each company include revenues from military sales, commercial sales and space sales. However, all of these corporations are involved in complex systems engineering and integration and are potential bidders for aspects of NASA's space exploration infrastructure. The table was derived by cross-referencing the Aviation Week "Top Performing Companies" rankings of aerospace and defense companies with total revenues above $1 billion (Aviation Week, 2010) with the top 100 NASA contractors (Federal Procurement Data System, 2011). Companies which appeared on both lists were deemed to have an appetite for government space projects and be large enough to handle complex system engineering. Companies which appeared on both lists but do not do extensive system engineering (L-3 Communications, Babcock International PLC and Textron) were not included.

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[2] These heuristic observations have been quantified more precisely in recent work on change propagation. See for example (Giffin et al., 2009).

Table 3: Aerospace contractors capable of handling large system engineering tasks

Contractor	Total Revenues (2009 or 2010)
Boeing	$64 billion
United Technologies	$54 billion
Lockheed Martin	$46 billion
Northrop Grumman	$34 billion
Honeywell	$33 billion
General Dynamics	$32 billion
Raytheon	$25 billion
Alliant Techsystems (ATK)	$4.0 billion
Teledyne Technologies	$1.6 billion
Orbital Sciences	$1.3 billion

Even if a handful of additional corporations may be capable of systems engineering and integration of large NASA systems, the total pool of contractors NASA has to choose from for complex systems is small compared to terrestrial projects like civil construction. The "oligopoly" (Szajnfarber & Weigel, 2009) in the space industry affects competition for government contracts and is an important factor to consider in developing an acquisition structure.

Technical Fact: The historical development time for space systems is approximately a decade.

An additional effect of complexity is long development times. While from a technical standpoint increased funding and political support can speed development, history indicates that development times of approximately a decade from initial funding to initial operations should be expected. Each of the missions have unique characteristics which make it hard to state the "decade in development" rule with certainty.

1. Apollo: 1961 to 1969. Apollo had relatively high political support, but the mission it attempted was also very technologically challenging for the times.
2. Shuttle: 1970 to 1981. The Shuttle program had lower political support than Apollo, but did not require the coordination of as many separate programs.
3. International Space Station: 1984 (as *Space Station Freedom* in President Reagan's 1984 State of the Union Address) or 1993 (as the *International Space Station* under President Clinton), to 2011 (scheduled) (General Accounting Office, 1994). The Space Station underwent numerous redesigns, fluctuating political support and had to meet the challenges of multinational cooperation.
4. Constellation: commenced in 2005, with first missions beyond LEO originally scheduled for 2017 (NASA, 2005). Constellation was potentially simpler technically than the earlier programs, but operated under a shrinking budget environment.

From the fact that acquisition structures take a decade to develop, two acquisition consequences can be distilled.

Acquisition Consequence 4: The acquisition must be effective over development times of at least a decade.

The acquisition structure must be able to operate over a decade. This is an important consideration because the corporations which begin work on the systems and products may need to be incentivized to remain in the aerospace business over that timeframe. Contingencies may be needed in the acquisition strategy to account for corporations which drop out of the program midway through.

Acquisition Consequence 5: The acquisition must deliver first flight within a decade.

The acquisition structure must deliver initial successes within a decade. This is an important consideration because some approaches to commonality would first construct "building blocks" and later build fully operational projects around these systems. If such an approach takes more than a decade it will involve a fundamental shift in the way NASA promises and delivers space hardware to its Congressional funders.

Technical Fact: NASA has extensive human spaceflight experience important for the success of future exploration missions.

NASA is still the *"world's greatest repository of space knowledge and experience"* (Augustine et al, 1990). Human spaceflight is an esoteric discipline carried out in few countries around the world, and much of the knowledge on successful human spaceflight is gained through experience. NASA has collected that experience through 50 years of human spaceflight. If the United States is to capitalize on its current leadership in human spaceflight, future systems should make the most of NASA's experience.

Acquisition Consequence 6: The acquisition strategy must allow NASA to impart its human spaceflight experience to the contractor.

The acquisition strategy should include mechanisms which give contractors the benefit of NASA's human spaceflight experience. Traditionally, this was accomplished through rigid specifications imposed by NASA for everything from wiring to safety factors to torqueing bolts. In part it was also driven through the insight process discussed in the next paragraph. These methods, while proven, are not the only methods for communicating NASA's experience. The acquisition strategy should achieve the same results but need not use the same techniques.

Technical Fact: Complex spacecraft are prone to complex failures. NASA is held responsible for these very public failures.

In writing on system architecting, Rechtin points out that *"complex systems fail in complex ways" (Rechtin, 1999, p. 105).* Space systems are not only complex, but they are often only fully tested for the first time in the totality of their operational environment with humans on board. Physical assistance from the ground is usually impossible. To minimize the chance of failure, the spacecraft must be designed, built and tested to be as reliable as possible.

The need for NASA to ensure reliability is compounded because NASA is deemed responsible for the failures of its contractors. The loss of Space Shuttles Challenger and Columbia were tragically spectacular. The ensuing investigations centered, in the public mind, on how well NASA performed its job, rather than how well contractors performed.[3] NASA, in the eyes of the media and the public, is responsible for all the systems which it funds.

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[3] In both cases the causes of the failure were assessed as partly technical and partly organizational. Both NASA and its contractors shared some responsibility, but the public overwhelmingly perceives failure on NASA missions as a NASA failure.

Acquisition Consequence 7: The acquisition strategy must give NASA confidence in the reliability of its contractors' design, manufacture and testing process.

NASA has historically worked closely with its contractors, even after the learning curve of the Apollo program ended and contractors were more experienced in the design of spacecraft. NASA's *"insistence on looking over all details"* and *"technical penetration into the industry"* was unchanged. This attitude started during Apollo, *"where there was trouble NASA was inclined to send in its personnel and its techniques, and it had the engineering and manufacturing expertise to make this sort of laying on of hands possible*" (Bromberg, 1999, p. 63). The insistence of strong oversight stemmed from the early days of the launch vehicle program when von Braun's engineering and manufacturing teams were organizationally very close. *"Rigid control of manufacturing became utterly critical. The smallest imperfection could and did lead to catastrophic failure"* (Johnson, 2002, p. 8). *"Contractors viewed the paperwork as an excessive burden, but NASA professionals viewed it as contractor penetration - an essential element in their overall culture"* (McCurdy, 1993, p. 117).

An acquisition structure which does not support NASA's cultural insistence on contractor insight is likely to meet significant resistance when it is implemented.

Technical Fact: Systems engineering and integration is performed best by those with experience in building the systems they integrate.

System engineering and integration on space programs involves a wide range of disciplines and skills, from writing technical requirements to managing contracts. Most agree that the quality of system integration improves if the integrator has had experience with the systems they are subcontracting for and coordinating. McCurdy states that the hands-on work *"sharpened technical skills and in the process expanded the capability of NASA employees to monitor the technical work of contractors"* (McCurdy, 1993, p. 34).

Augustine made the same point in his 1990 report: *"The dilemma is that the best systems engineers are often those with a great deal of experience...but how can one get scar tissue if one is confined to studying, analyzing and overseeing the work of others? The answer, by and large, is that one cannot"* (Augustine et al, 1990).

Acquisition Consequence 8: The system integrator(s) must have recent or ongoing engineering experience on human space systems.

The need for hands-on experience has acquisition consequences. The acquisition structure should recognize that the best system engineers have had recent hands-on experience. A good acquisition structure will give the integration role to an organization with that experience, and find ways of keeping that experience current.

Technical Fact: Operation of space infrastructure is costly and has historically resulted in unsustainable architectures.

The final twist to NASA's engineering task is the delicate balance between development and operations. In the early programs such as Mercury or Apollo, operations was a stay of up to week in space and a logical extension of the engineering development. Each mission achieved very different objectives and most went to a new location. However, in the Space Shuttle and International Space Station programs similar missions are performed repeatedly. In those programs, NASA was faced with difficult but not revolutionary missions. Despite flying the Shuttle almost 140 times, processing a Shuttle for flight *"requires that 1.2 million separate procedures be accomplished,"* (Augustine et al, 1990, p. 18) across 87 "critical systems"

(General Accounting Office, 2000) by 12,500 workers and $1.5 billion worth of fixed facilities (Augustine et al, 2009).

Developing firmer estimates of the relationship between development and operating costs of human spaceflight programs is difficult. The Mercury and Gemini programs mixed military and civil funding; the Gemini program was largely operational testing in support of Apollo development; and the Apollo program did not have continuous operations as its goal. The International Space Station has had humans aboard for most of its development time, which makes it difficult to separate development from operating costs. It is also a multi-national development which mixes in-kind contributions such as Russian Proton launches with more concrete development costs of US modules.

The Shuttle, although roundly criticized for its high operating costs, remains the one vehicle where development and operations phases were largely separated and a comparison can be drawn. Augustine et al (1990) cites the development cost of the Shuttle at $27.8 billion in 1990 dollars, and Augustine et al (2009) cites the total cost of the Shuttle at $129.5 billion in 2009 dollars. The 1990 Augustine figure is $40 billion in 2009 dollars' yielding an approximate operating cost of $90 billion over 30 years of operation, or $3 billion per year. The development cost of $40 billion was spread from 1970 (when the RFPs were released (Bromberg, 1999)) to first flight in 1981, making an average cost of approximately $4 billion per year, comparable to the operation cost.

McCurdy was correct in finding that a *"tendency toward routine operations poses a special challenge for a research and development organization like NASA"* (McCurdy, 1993, p. 142).

Acquisition consequence 9: The acquisition strategy must achieve a balance between development and operation costs.

The balance between operations and development has acquisition consequences. Technical trades made during development, like those that led to a semi-reusable shuttle, have a lasting impact on operational costs. Acquisition strategies which encourage contractors to make development-operation trades in the region NASA would like (wherever that may lie) are preferable. As with the shuttle, this acceptable region may change during development.

In sum, the unique technical features of human spaceflight give rise to unique acquisition requirements. However, these technical achievements are reached with the help of industry, and the nature of the industry-NASA relationship is critical to developing effective acquisition structures.

Industrial Features of Human Spaceflight Architectures

The nature, number, and motivations of the contractors which serve NASA are of critical importance in determining acquisition structures for commonality. After all, an acquisition structure is designed to apportion tasks in the best way between NASA and private industry. Szajnfarber writes that *"the space market structure is relatively unique in that it is effectively a monopsony (single buyer) oligopoly (few sellers) contract market,"* (Szajnfarber, 2010) and an understanding of this unique market underpins the conclusions to this thesis.

Industry Fact: The US Government is the only customer for NASA's Human Spaceflight Architecture beyond LEO.

Szajnfarber states that for space architectures there is *"only a single viable customer in most cases"* (Szajnfarber & Weigel, 2009). This is particularly the case for elements of an exploration architecture which extend beyond low-earth-orbit (LEO). Elements beyond LEO cannot be repurposed for commercial uses such as Earth observation and communications or, as yet, tourism.

Acquisition Consequence 10: The acquisition strategy must not depend heavily on funding from non-government sources at any point in the product lifecycle.

The acquisition strategy should not try to draw funding by being marketable to private interests. Space exploration does not yet produce commercially valuable outputs (in the sense that they can be marketed and sold) at the same order of magnitude as the costs of exploration. The intangibles of exploration, like national prestige, inspiration, education, curiosity and scientific discovery (MIT Space Policy and Society Research Group, 2008) are valuable only to governments and do not yet represent bankable commodities.

There are currently some potential synergies between commercial interests and human space exploration. For example, commercial interests require launches of up to about 25 metric tons to LEO and it is possible to spread the costs of launch vehicle development across both commercial and exploration launches.

It is possible that in the future commercially valuable resources or facilities may exist beyond Earth. Such a discovery will change the fundamental nature of human activity beyond Earth, however, it is likely that significant exploration will need to take place before such a discovery is made. Predictable markets like space tourism are likely to do little for exploration in the medium term given that they must necessarily operate in reasonably well understood environments like sub-orbital and LEO. Possible commercial markets opened up by exploration, like on-orbit refueling, will still be paid for from the government dollar, even if the method of achievement is left to industry's innovation.

Industry Fact: The production runs of the next human spaceflight architecture are likely to be one or two of each element per year over a period of time that cannot be easily predicted.

The number of elements produced for human spaceflight architectures are small. For Apollo elements, *"the actual run might amount to one or two dozen items, and even these...would differ one from the other"* (Bromberg, 1999, p. 61). The situation was worse with the Shuttle where only five fully-functional Space Shuttle Orbiters were produced, although the boosters, main engines and external tanks need replacement on various time intervals.

The quantity of exploration elements required is also uncertain because of uncertainty over the number of missions to be flown. The final Apollo missions were cancelled. No sustained program of moon landings followed it. The number of Space Shuttle launches fell many hundreds short of initial predictions. The Constellation architecture was more open ended and reflected a drive towards sustainable, ongoing missions, however the program was cancelled after just a single test flight of the Ares I-X.

Acquisition Consequence 11: The acquisition strategy must allow corporations to make a profit despite small production rates and uncertain production quantities.

In the long run, NASA contractors must make profit. In the commercial case studies described in Chapter 4, managers expressed their worry that suppliers under profit pressure would shortcut on quality. The same applies to NASA's contractors. Additionally, over the decade-long time scales of exploration developments, contractors who fail to profit from NASA contracts will go out of business or move to other industries.

The need to make a profit may appear obvious, but aerospace companies do not traditionally profit on development type contracts. The short production runs on exploration elements necessitates a different bid strategy by contractors to that which might be used for aircraft or ships. *"Aerospace companies were used to making their money on production runs of hundreds...it was common practice to buy in by underbidding on the development, with the idea of making up the losses on subsequent hardware contracts"* (Bromberg, 1999).

The need extends below the prime contractor level. The acquisition strategy must keep small corporations which produce niche pieces of hardware needed only for the exploration program in business. If these corporations are not maintained, then development of new units and maintenance of existing units is difficult. *"Over the years, the Shuttle Program has experienced many instances of suppliers dropping off unpredictably, making supply chain management more difficult and costly...the average mitigation cost is between $200,000 and $700,000"* (Government Accountability Office, 2007a).

The relationship between NASA and industry shapes the types of acquisition structures which are likely to be effective. Equally relevant are the influences of politics, at both the organizational level within NASA and at the federal level.

Political Features of Human Spaceflight Architectures

This section examines two types of politics. First is a consideration of the organizational politics within NASA. Second is a consideration of the consequences of national politics. The achievement of political goals is NASA's reason for existence. NASA's funding comes from Congress, and as such an acquisition structure must take into account the political imperatives which shape NASA.

Political Fact: The ten NASA centers do not function as a cohesive unit.

NASA centers will sometimes place the interests of the center above the interests of NASA as a whole. This is not intended as a criticism, but rather as a statement of a fact that applies to every large organization. Centers have traditional areas of expertise which they will promote, market and protect. Centers will tend to prefer job losses at other centers than their own.

After describing NASA as a *"confederation of subcultures"* (p. 7), McCurdy goes on to highlight inter-center rivalry at its worst on the Space Station program: *"Field officials...preferred the low level of supervision created by the lead center approach. [They] wouldn't even give Houston the courtesy of responding to their communications, much less recognizing them as being in charge" (McCurdy, 1993, p. 131).*

Improved telecommunications now blurs the physical lines between the centers more than previously. However, the searching budget pressure and lack of clear goals at the present time is likely to exacerbate a desire to promote the worth of individual centers. It is not possible to say whether the problem is better or worse than described by McCurdy, but it is certain that it still exists.

Acquisition Consequence 12: The acquisition strategy must overcome inter-center parochialism.

The acquisition strategy must acknowledge that information sharing across NASA is not going to be perfect because of the geographical and cultural separation of the centers. This is important from an acquisition point of view, because the traditional approach to dealing with this fragmentation is to exacerbate it by allocating different projects to different centers. The 1990 Augustine Committee were cautious about this approach warning that this was *"exactly the opposite of generally accepted management philosophy that argues for minimizing interfaces, the 'nooks and crannies' where problems seem to breed"* (Augustine et al, 1990, p. 128).

Political Fact: Closure of any NASA centers will be politically difficult.

NASA is also strongly supported by local interests within states where NASA is a major employer. This means that any exploration infrastructure must use a network of NASA centers, contractors and supply chains which is geographically diverse. Any downsizing or closure of centers will be fought hard. Szjanfarber observed this on the center level: *"NASA has chosen to prioritize maintaining "10 healthy centers" versus only assigning work to the center where the historical experience for that work resides"* (Szajnfarber et al., 2009) Bromberg saw the same force at work in the International Space Station work allocation: *"Political considerations dictated that as many centers as possible get a piece of the action."* (Bromberg, 1999, p. 180).

Acquisition Consequence 13: The acquisition strategy must allocate some work across all ten NASA centers

An acquisition strategy which utilizes all centers will cause less political difficulty than strategies which require significant downsizing of particular centers. Inevitably there is some adjustment with any new dominant program, however strategies like those adopted for Constellation and International Space Station which put different centers in charge of different aspects of the exploration infrastructure are more politically palatable than strategies which focus the majority of work at a single NASA center. This is one of the most obvious areas where the NASA acquisition realities and the most desirable approach for commonality conflict.

Political Fact: Funding for NASA will vary over time

Even in the best run program, the funding for the development of multi-decade exploration architectures will vary as priorities within government change. As examples of funding changes over the life of programs, Bromberg points to the construction of the Shuttle under *"tight financial constraints...continually under attack from Congress and OMB"* (Bromberg, 1999, p. 95). The International Space Station was blown closer to the rocks of cancellation than perhaps any other completed space architecture, and McCurdy notes that *"between 1985 and 1991 they redesigned space station Freedom no less than five times in their efforts to find a configuration that the politicians would fund"*. Logsdon argues that Apollo's status in Congress as a fiscally untouchable memorial to a slain president saved the program from deeper criticism and funding cuts which may have jeopardized the 1969 moon landing (Logsdon, 2010).

Acquisition Consequence 14: The acquisition strategy must be robust to year-by-year changes in funding

The acquisition consequence of consistently fluctuating budgets is that such uncertainty should be planned for. An acquisition strategy which acknowledges that budgets will fluctuate and plans accordingly in advance will more realistically reflect the nature of NASA's acquisition task. While there remains *"little hope of budget stability"* (Augustine et al, 2009, p. 113), a good acquisition structure (together with strong leadership) can prevent the knock-on effect of a *"frequent need to revamp major programs"* (Augustine et al, 1990).

Political Fact: NASA's support in Congress will be enhanced if contracts are awarded across diverse geographical regions and several different contractors

NASA's Congressional support depends in part on the jobs it creates, though the 2009 Augustine report warned *"it is demeaning to NASA's professionalism to treat the human spaceflight effort as a "jobs" program" (Augustine et al, 2009, p. 112).* In September 1961 *"the lore was that NASA would not give more than one major contract to any single firm. [Contracting would be* *wide] in terms of companies and geographic locations. This would help ensure a cadre of capable firms for future contracts, and also build political support for its expanding space efforts."* (Bromberg, 1999). Little has changed. Figures showing the diversity of corporations with responsibility for elements on space programs are shown below for the Apollo program, the Space Shuttle Orbiter and the main Constellation program elements (Levine, 1982) (NASA, 1976).

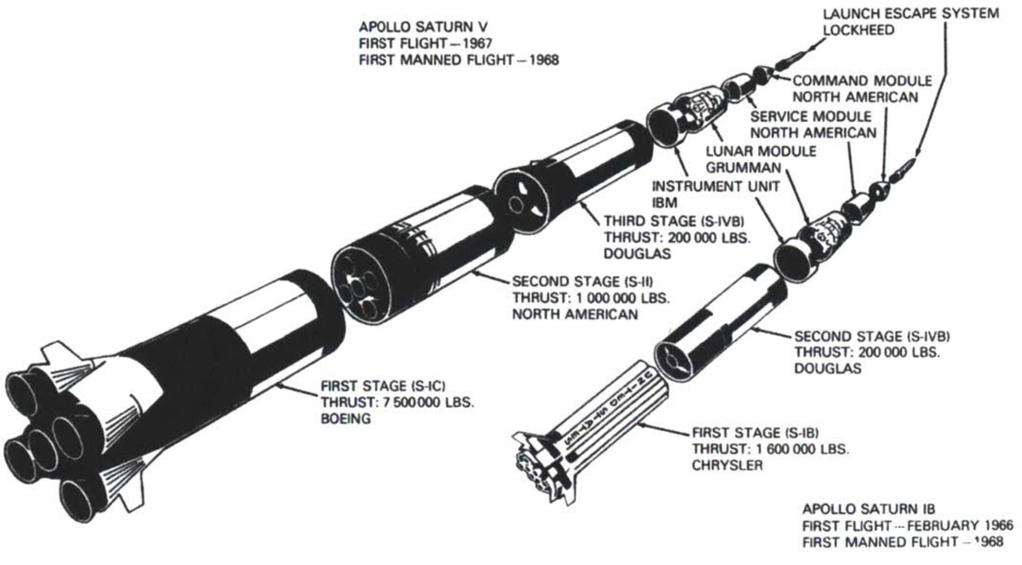

Figure 4: Prime contractors for elements of the Apollo Program (from Levine)

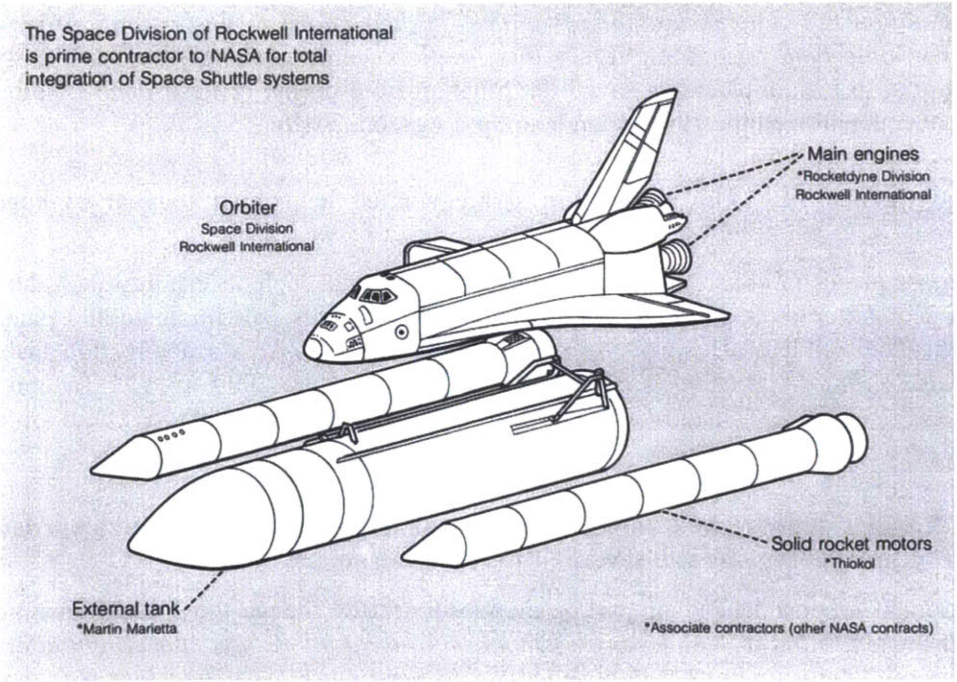

Figure 5: Space Transportation System Contractors (NASA)

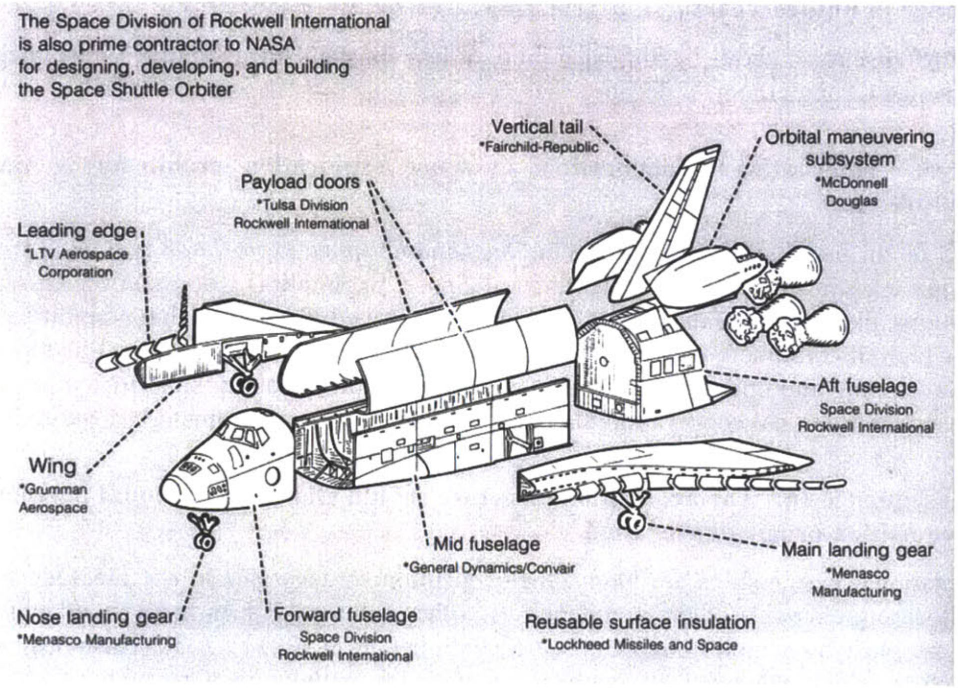

Figure 6: Space Shuttle Orbiter Contractors (NASA)

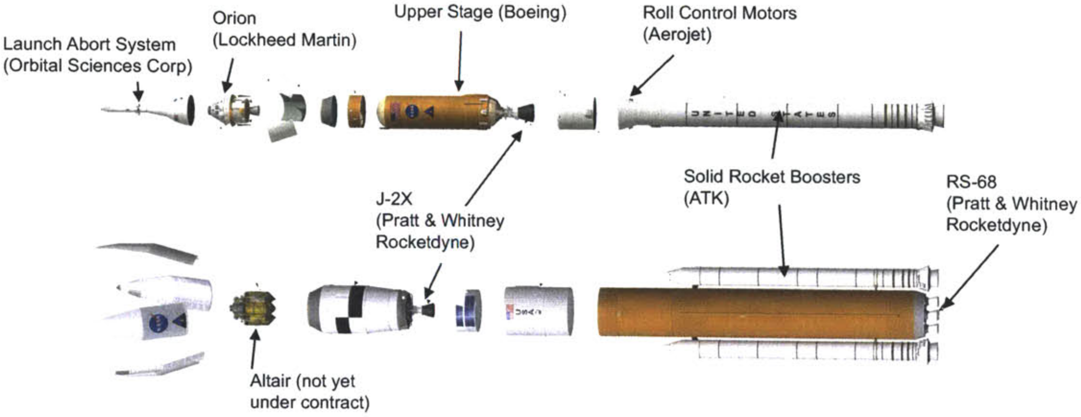

Figure 7: Constellation Program contractors (image: NASA with annotations by the author)

Acquisition Consequence 15: The acquisition strategy must allow work to be divided between the major aerospace contractors

An acquisition strategy which partitions work so that it can be parceled out to a variety of contractors is politically preferable to one where a single contractor has the lion's share of the work. Even on an architecture like the Space Shuttle, where the highly integrated nature of the design would appear to indicate a single contractor, George Low worked with North American Aviation / Rockwell which won the prime contract to *"ensure that at least some of the money would be passed through to the losers" (Bromberg, 1999)*. The diversity of contractors is clear from Figure 5 and Figure 6.

Avenues of Change in Future Years

Despite the features discussed above having been more or less constant since the mid 1960s, there is prospect for change through the next decade.

Possible Change: International cooperation on space exploration architectures may increase over future years

There appears to be an increasing realization that "*Sustainable space exploration is a challenge that no one nation can do on its own*" (International Space Exploration Coordination Group, 2010, p. 2). Nations like Russia, Japan, Europe, China, India and Canada all have significant space expertise which, if combined, may solve the US difficulty identified in the Augustine report of the costs of developing and operating space systems (though not without raising difficulties of its own). Increased international cooperation may be a feature of space programs in the future.[4]

Acquisition Consequence 16: The acquisition structure should allow international partners to fit into the acquisition program over time.

Given that international partnerships are likely, the acquisition strategy should not preclude the possibility of allocating elements of the architecture to other nations. For an analysis of which elements could be built by which countries, see Szajnfarber et al (2011) . For instance, an acquisition structure which allocated all exploration elements initially to a particular NASA center for further contracting would likely preclude international cooperation along the "critical path" (a desire of many potential partners). It would score poorly against this acquisition consequence.

Possible change: Commercial space companies may become increasingly capable and have customers other than the US government

There is increased interest in the products produced by commercial space companies (loosely defined as those seeking a non-government market or developing for the government market on private funding). SpaceX is the most prominent, but the inflatable modules developed by Bigelow Aerospace, the engine technology behind Xcor and the vertical take-off and landing systems developed by Masten Space Systems would all have places in an exploration architecture. SpaceX is midway through development of a family of human-rated launch vehicles where the heaviest of the vehicles (Falcon 9 Heavy) would have a payload of nearly 30 metric tons to low Earth Orbit, and is developing the Dragon crew capsule (Dreyer, 2009). Commercial companies are investigating space options for transport and tourism (Chandler, 2007). While these systems are presently dwarfed by the government investment in space exploration infrastructure, private development is a fast growing industry. If the high growth trend continues, the commercial industry may have an effect on NASA's exploration infrastructure. Pelton overviews some of the more wide-reaching potential contributions by private space companies (Pelton, 2010).

Scott Pace summarized the uncertain future of commercial spaceflight in a recent interview: *"This generation of companies— SpaceX, Bigelow, Virgin Galactic, and a number of others—is the strongest and the best that we've seen to date. They have made progress, but if history is a guide, most will die"* (Pace, 2011).

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[4] For a variety of perspectives on blending domestic US and international space programs, see for example the focused segment in Volume 27, Issue 1 (2011) of *Space Policy*

Acquisition Consequence 17: Acquisition strategies should allow the participation of commercial space companies when the capabilities of those companies are proven.

The acquisition strategies should take the developing commercial sector into account. There should be scope within the acquisition structure to include commercial developments, once proven, into the exploration architecture. For instance, an acquisition structure which awarded most of the contracts at the project outset for long durations would score poorly on its flexibility to allow commercial space companies to participate.

Summary

NASA's acquisition strategies need to work with the organization and its environment. This chapter has identified the technical, industrial and political realities of NASA's mission, and how those realities may change over the next phase of human space exploration. Table 2 summarizes the key conclusions of this chapter. These acquisition realities will be used in Chapter 5 to assess the acquisition strategies based on how appropriate those strategies are to NASA's mission.

2.2 COMMONALITY OVERVIEW AND IDENTIFICATION OF BEST PRACTICE

Introduction

The previous section examined the technical, industrial and political environment which constrains NASA's acquisition strategies. Fitting the NASA environment is not enough for a successful commonality strategy however, and this section will identify the current best practice for pursuing commonality. Ultimately, the aim of this thesis is to find a strategy which is close to best practice for commonality *and* which fits the NASA environment.

This section will first overview the extensive work on best practice for commonality which has been summarized and extended by Boas and Rhodes. Then the section will provide additional high-level observations about commonality developed during this thesis, leaving the detail to the descriptions of the case studies in chapter 4. The section closes by providing process maps for commonality. The purpose of the process maps is as checklists of good commonality practice, and each acquisition strategy will be evaluated on how well it allows each process to be executed.

Overview of existing analysis of commonality

At the outset of this examination of commonality, it must be made clear that commonality is not a goal in itself. Making two products more or less common does not make either intrinsically faster, better or cheaper. However, in some commercial industries commonality is an established way to develop products faster, at lower cost, and with higher reliability. Such achievements would be attractive to NASA.

Commonality has been defined in a number of different ways. Boas looked at the physical instances of commonality and defined it as *"the reuse and sharing of assets such as components, processes, technologies, interfaces and/or infrastructure across a product family"* (Boas, 2008, p. 12).

A product "family" is a set of products which for which the "customer needs" may overlap and commonality may be possible (Boas, 2008). Hofstetter describes the same in terms of "engineering needs" and uses the term "portfolio" to describe the set of products finally produced (Hofstetter, 2009). In this chapter we will use Boas' nomenclature. A "variant" is a particular type of product in the family. For example, the Delta launch vehicles are a product family, and the Delta IV Heavy is a variant. Variants have some commonality with other products in the family.

In these definitions, it is important to draw a distinction between commonality between products within a family, and commonality between products used elsewhere in industry. The first commonality philosophy is reuse and platforming within a family (simply referred to as "platforming"), the second commonality philosophy is the use of "commercial off-the-shelf" (COTS) parts. This thesis examines "platforming" type commonality rather than COTS commonality for several reasons. The primary reason is that platforming is more powerful (assuming it can be well executed, a non-trivial assumption because platforming is generally more difficult). Platforming in spaceflight applications is more powerful because it deals with system-level commonality, while COTS deals largely at the component level.

Figure 8 shows the advantages and disadvantages of commonality throughout a simplified product lifecycle. The figure is a consolidation of information presented by Boas, Hofstetter and Rhodes and also incorporates comments made by interviewees during this thesis. Table 4 and Table 5 describe the advantages and disadvantages in more detail.

Three key points can be drawn from Figure 8. First, commonality has multiple effects on all stages of the product lifecycle beginning with product strategy decisions and carrying through to operations.

Second, commonality in all stages of the product lifecycle involves a weighting of advantages and disadvantages. Each lifecycle phase has boxes above the middle black line indicating advantages and boxes below indicating disadvantages.

Third, commonality involves a multi-objective trade-off. Boxes shaded purple indicate a performance effect, while boxes left unshaded affect cost and schedule. For example, commonality improves survivability in the operating phase, but at the expense of an ongoing cost of managing commonality. Therefore examining whether commonality is beneficial in any particular instance is not straightforward.

Figure 8 presents the advantages and disadvantages from the perspective of the entire product family. The perspective of variants within the family may be a subset of this full set of advantages and disadvantages. This is particularly the case when the developments are offset in time, which Boas showed occurs in all complex product families.

Figure 9 shows the perspective of the first variant in time when there is offset between the variants. When the development of variants in the product family is offset in time, the first variant is likely to perceive commonality as less advantageous than will later variants. For example, the first variant might be required to design a flight computer which exceeds its own needs by including additional interface ports. It incurs the additional design cost without any performance benefit. The first variant will also not obtain any operating benefit until the subsequent development projects with which it was designed to be common occur. Cancellation of later projects will reduce the value of the investment of the first product in commonality. The fact that the first-in-time variant sees significant downside to commonality was highlighted by Boas, but Figure 8 and Figure 9 taken together powerfully illustrate how strong this phenomenon could be.

Conversely, the later variants in a product family usually achieve commonality benefits earlier, for example by taking advantage of earlier designs. In the human spaceflight sector, it is very unusual for any designs to begin with a purely clean sheet (see for example the launch vehicle case studies in Chapter 4), and designs usually reuse some previous technologies both for cost and risk reasons.

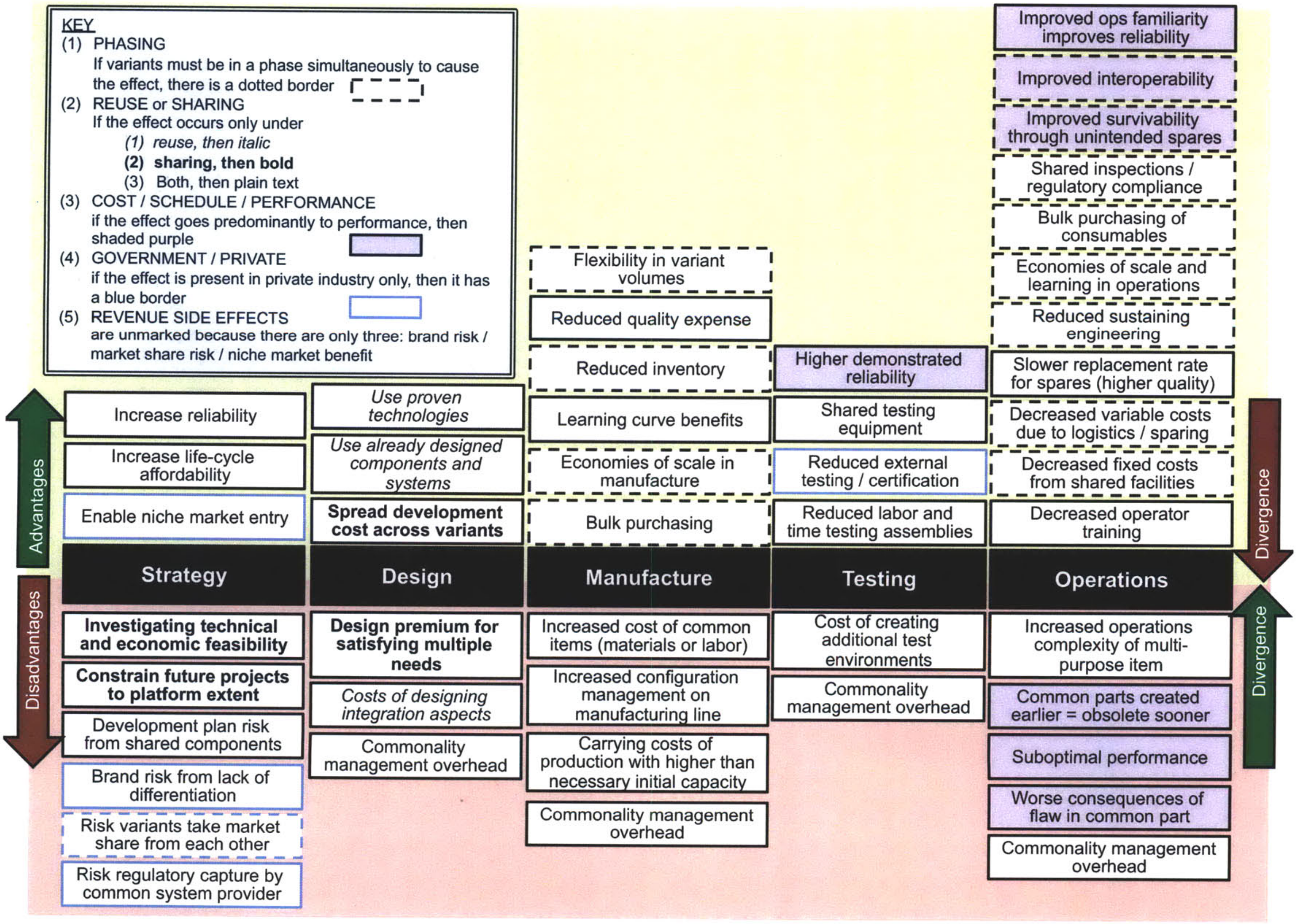
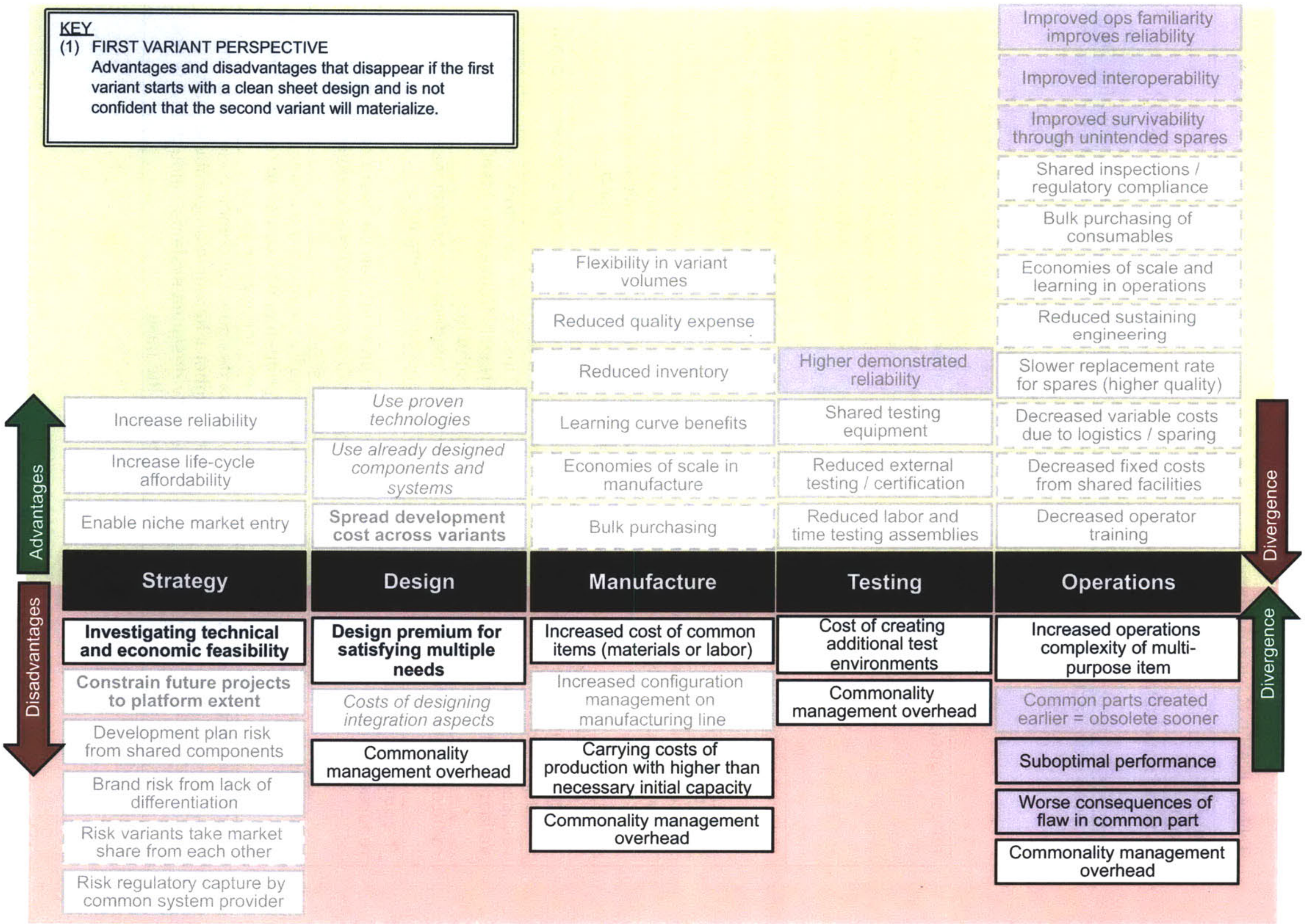


Figure 8: Commonality advantages and disadvantages through the product life-cycle



KEY
(1) FIRST VARIANT PERSPECTIVE
Advantages and disadvantages that disappear if the first variant starts with a clean sheet design and is not confident that the second variant will materialize.

	Strategy	Design	Manufacture	Testing	Operations
Advantages	Increase reliability Increase life-cycle affordability Enable niche market entry	*Use proven technologies* *Use already designed components and systems* **Spread development cost across variants**	Flexibility in variant volumes Reduced quality expense Reduced inventory Learning curve benefits Economies of scale in manufacture Bulk purchasing	Higher demonstrated reliability Shared testing equipment Reduced external testing / certification Reduced labor and time testing assemblies	Improved ops familiarity improves reliability Improved interoperability Improved survivability through unintended spares Shared inspections / regulatory compliance Bulk purchasing of consumables Economies of scale and learning in operations Reduced sustaining engineering Slower replacement rate for spares (higher quality) Decreased variable costs due to logistics / sparing Decreased fixed costs from shared facilities Decreased operator training
Disadvantages	**Investigating technical and economic feasibility** **Constrain future projects to platform extent** Development plan risk from shared components Brand risk from lack of differentiation Risk variants take market share from each other Risk regulatory capture by common system provider	**Design premium for satisfying multiple needs** *Costs of designing integration aspects* Commonality management overhead	Increased cost of common items (materials or labor) Increased configuration management on manufacturing line Carrying costs of production with higher than necessary initial capacity Commonality management overhead	Cost of creating additional test environments Commonality management overhead	Increased operations complexity of multi-purpose item Common parts created earlier = obsolete sooner **Suboptimal performance** Worse consequences of flaw in common part Commonality management overhead

Figure 9: Advantages and Disadvantages of commonality from the first variant perspective

Table 4: Benefits of commonality

Benefit	**Reason**
Cost	
reduced development cost	Commonality can reduce the number of separate development projects, or the amount of effort on development projects after the first
reduced manufacturing cost	Economies of scale in component procurement; reduced variation in the tooling and manufacturing equipment required for the product family spreads fixed, non-recurring capital costs; lower inventory costs for purchased common parts
reduced operating cost	Sharing operating resources like ground facilities or maintenance plants spreads fixed recurring costs over more products; variable recurring costs are reduced through economies of scale and learning; common products share common spare parts, reducing spares and logistics costs
reduced product volume risk	Common components can be allocated to any of the variants, reducing the loss associated with a single variant performing poorly
Schedule	
reduced development time over the whole product family	In design, reuse of well understood elements allows faster design; in production, manufacturing multiple identical elements becomes faster due to learning
Cost and schedule	
reduced development risk over the whole product family	Reuse of proven technologies; fewer separate development projects
reduced product verification and validation for later products	Reuse of testing infrastructure reduces costs; reuse of results from earlier identical products reduces schedule
reduced training time	Common interfaces or operational procedures reduce operator training time
Product performance	
reduced operational risk	Common products can be operated in common ways, reducing operational complexity and operator error
increased survivability	Commonality improves the chances of success in using non-intended spares to replace critical parts in emergency situations
improved interoperability	Systems designed on common elements often have higher inherent interoperability than uniquely designed systems, though this is not always the case

Table 5: Drawbacks to commonality

Drawback	Reason
Cost	
Increased cost and risk for initial production	Engineering a part to be common across multiple products often makes the part more complex
Increased cost for the initial product if future variants do not appear	Commonality benefits are often based on sharing with future variants; if these future variants do not appear then the added cost and complexity of making the parts common is wasted
Cost and Schedule	
Increased cost and time for the design and manufacture of the first unit	The process of identifying and managing commonality increases the cost of producing the first unit
Increased risk of obsolescence	Technology or market changes may make the common component obsolete, necessitating an upgrade of the entire product family
Product performance	
Sub-optimal performance	Common parts imply either overperformance in one variant or underperformance in another variant, because the part is not optimized for the particular use case
Increased performance risk	A single design failure will affect more products if it occurs in the common part
Increased risk during operation	Common parts may be more complex and therefore more prone to failure

Boas also points out that implementation of retroactive commonality is unusual and expensive. He traces this to the cost of a simultaneous change to two projects at different stages of the development cycle, shown in Figure 10. The blue line represents the time variance of the cost of change for the first project, and the red line for the second project. At the point in time when an engineering change is contemplated, the cost of making the change is higher for the first project than for the second project. This means that for a certain range of changes where the cost of not changing the project (in terms of performance, operating cost or the like) is greater than the cost of change of the second project but less than that for the first, change will only be implemented on the second project. The implication of this for commonality implementation is that commonality must be well planned from the start.

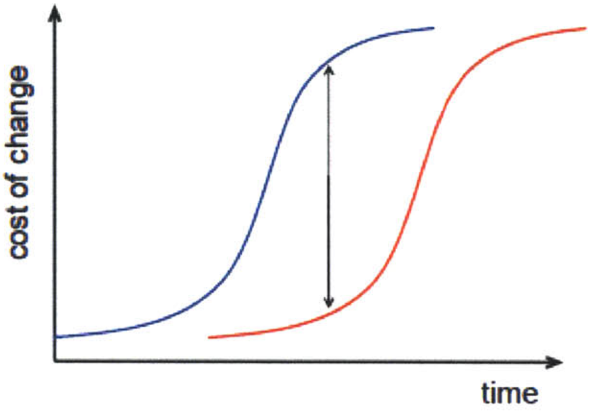


Figure 10: Different change costs at different points in development make retrospective commonality difficult to implement (Boas, 2008)

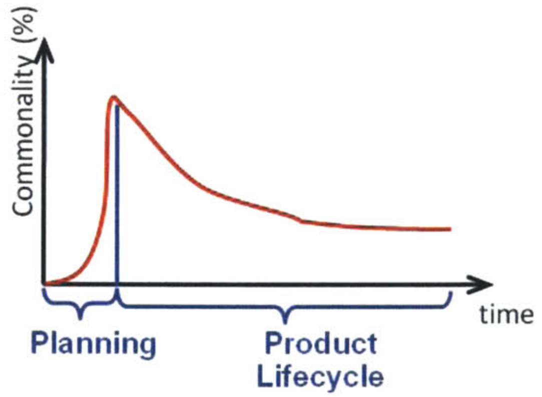


Figure 11: Divergence occurs through the product lifecycle (Boas, 2008)

Boas found that the amount of commonality throughout the product lifecycle always decreases after an initial planning phase, as shown in Figure 11. Boas coined the term "divergence" to represent the difference between the initial planned commonality of a product family and the realized commonality. He stated that divergence could occur for both acceptable and unacceptable reasons, summarized in Table 6. Rhodes showed how active management throughout the development cycle is an effective tool in the NASA context for managing divergence, minimizing unacceptable reasons for divergence.

Table 6: Acceptable and unacceptable reasons for divergence (from Rhodes 2010)

Acceptable reasons for divergence
Technology developments mean that a better solution for the lifecycle of the whole family has been identified
Market change necessitates a different second product than first anticipated
Learning through development of the first product suggests changes for the second product
Unacceptable reasons for divergence
Divergence to make unnecessary performance improvements unique to that variant
Divergence to improve the cost or schedule of that particular variant, while increasing the family costs.

In analyzing the management of commonality projects, Rhodes developed a three-phased framework based on the time progression of all commonality projects. He showed that an effective commonality plan should consider three phases:

- **identify** commonality opportunities for technical feasibility
- **evaluate** technically feasible opportunities for financial and other net benefit
- **implement** technically feasible, net beneficial opportunities

Rhodes pointed out that failure in any one of these steps results in less than optimal commonality. He presented a set of detailed heuristics and tools for managing commonality in each of these stages.

Boas presented a commonality framework which complements the approach of Rhodes. Instead of looking at the process steps in developing commonality on a project, Boas divided the commonality strategies into three types, based on the relationship between the elements in the family of common products. A stylized representation of the difference between the strategies is shown in Figure 12. To explain the figure:

- Reactive reuse simply recognizes and implements opportunities to use elements that have been developed in the past. *The development of the first system does not acknowledge the needs of the second.* An example of reactive reuse is the use of the Crawlerway at KSC for both Saturn V and Shuttle. In the context of developing space infrastructure, the interviews in Chapters 3 and 4 showed that reactive reuse is generally used where the rate of improvement in performance from technology is low, where reliability is best proved through flight heritage and high reliability is required and where manufacturing rates are low.
- Building block commonality occurs when a small number of particular modules, usually high-value, are *deliberately made common across the variants in the family*, but

independent development takes place on all other aspects. An example of building block commonality is the use of the J-2X upper stage engine across both the Ares I and Ares V. Building block commonality works well where new systems need to be developed because of technological progress or performance requirements, but all systems have similar operational environments.

- Widespread forward commonality occurs when modules are made common plus *attempts are often made to identify other opportunities for commonality* such as component, technology or process commonality. Commonality opportunities are implemented on some systems and divergence occurs on other systems on an ongoing basis to achieve optimum commonality levels over time. An example of widespread forward commonality is the Joint Strike Fighter development. Widespread forward commonality is most appropriate in situations where there is widespread potential component level commonality across different systems in addition to system-level commonality, and where there are significant benefits to commonality in later stages of development, for example manufacture or operations. While divergence is the dominant process, it is offset to a small degree by the continuous identification and implementation of new commonality opportunities (referred to as "convergence").

Boas points out that the best strategy is project dependent. For example, one of Boas' concluding recommendations was *"as time offsets between products increase, focus efforts on the intelligent reuse of existing assets rather than on enabling future commonality."* Boas saw all three of these strategies in organizations where a single corporation was charged with developing a family of common products.

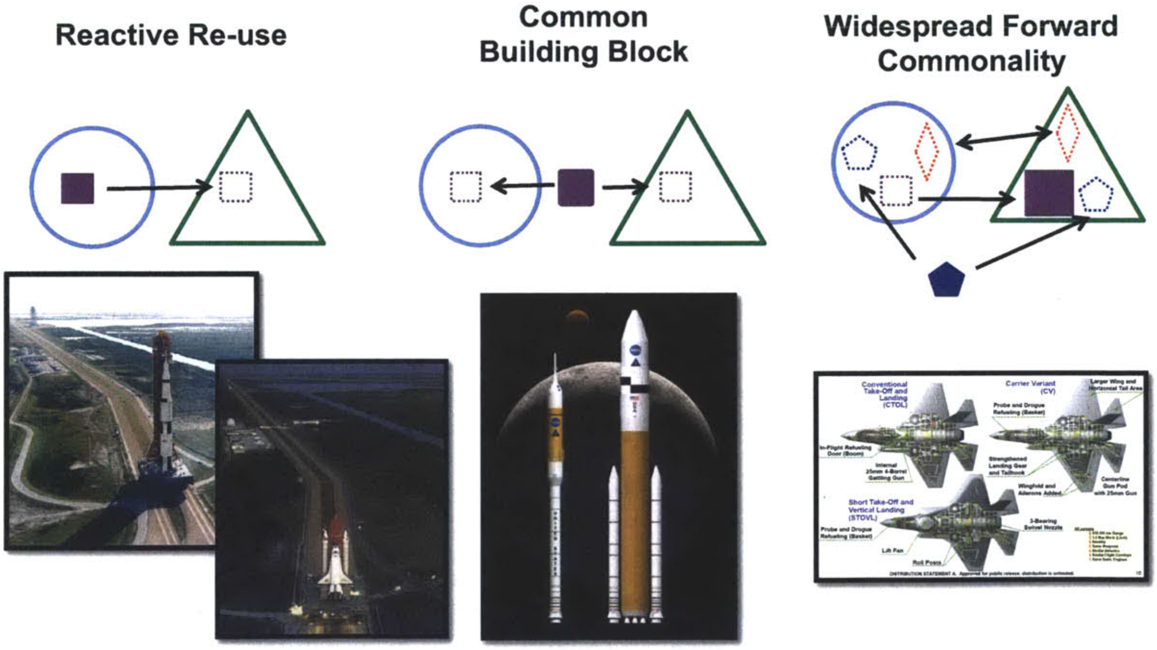


Figure 12: Boas' classification of commonality approaches

Before leaving the threefold classification of reactive re-use, common building block and widespread forward commonality, it is worth illustrating how reactive re-use and common building block strategies apply to a real NASA example.

Example of reactive re-use and building block commonality within NASA

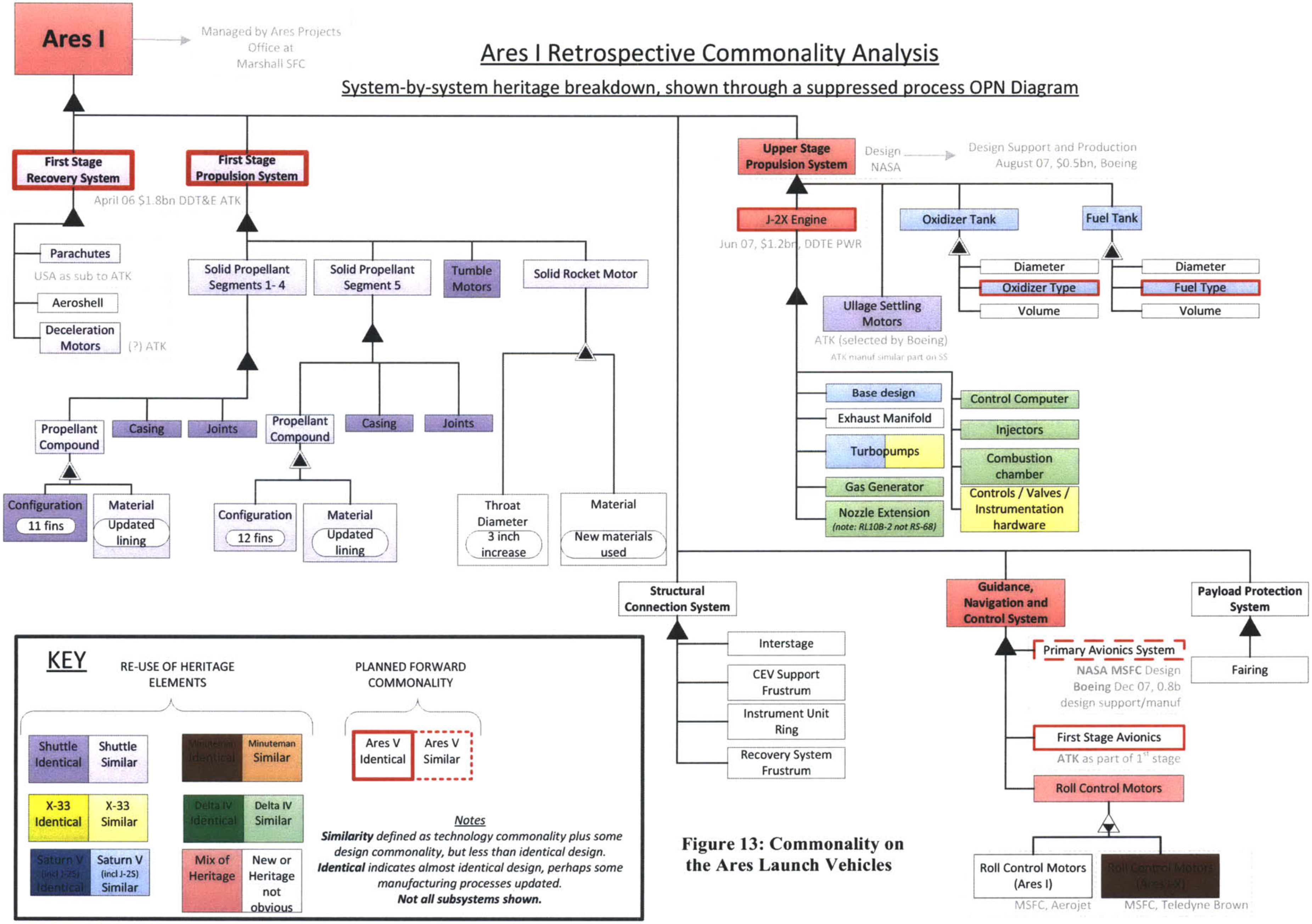
As a starting point in analyzing NASA commonality, it is important to recognize that NASA architectures are not based around a single type of commonality. Rhodes, for example, saw reactive reuse and building block commonality in his three NASA case studies. A second example was undertaken in preparation for this thesis on the Ares I launch vehicle, and its commonality forward in time to the Ares V launch vehicle. The example is shown in Figure 13 and illustrates three things.

First, reactive reuse is widespread on the launch vehicles. Each shaded box indicates commonality with previous launch vehicle systems. The color of the shading shows the source of the commonality.

Second, most systems have been modified from their original form as they were reused. This changes the system from being completely common into a "similar" or "cousin" part.

Finally, building block commonality is used at high levels of the project. The aggregations boxed in red are intended for direct reuse on the Ares V. Systems intended for reuse with modification are boxed in dashed red.

The example is also a motivation for this thesis. The organizations developing each of the systems are shown in grey around the system. There is a network of contractors with almost no commonality between the systems developed by different contractors. The research in this thesis aims to evaluate the effect of the network of contractors on the commonality that can be developed.



Notes

***Similarity** defined as technology commonality plus some design commonality, but less than identical design.*
***Identical** indicates almost identical design, perhaps some manufacturing processes updated.*
Not all subsystems shown.

Figure 13: Commonality on the Ares Launch Vehicles

Observations on commonality culture and commonality's interplay with other architecting strategies

Boas wrote that commonality culture is a *"culture of designing new by exception rather than default"* (Boas, 2008, p. 214). Boas only observed this culture in an organization practicing widespread forward commonality. As a result, it is tempting – but incorrect – to consider commonality culture and widespread forward commonality to be synonymous. In light of the work undertaken for this thesis, it is more correct to say that a commonality culture can complement any one of the three family strategies, and it will choose the most appropriate strategy at any point. For example, the third case study in Chapter 4 demonstrated a commonality culture predicated largely on reuse.

Commonality is not the only architecting strategy available to design good architectures. Table 7 shows three strategies often considered in the context of architecting space exploration. A modular architecture, an open architecture and an interoperable architecture are considered. The modular architecture closely parallels building block commonality by dividing the architecture into re-usable modules. Its approach is strongly complementary to commonality. An interoperable architecture is designed to permit predictable interaction between different systems, usually to form a network. Commonality of interfaces or communication protocols is often used as a way of obtaining commonality, although commonality is neither necessary nor sufficient for commonality. In this way, interoperable architectural approaches are complementary to commonality approaches.

Open architectures, however, are not. Open architectures depend on a proliferation of isolated but competitive designs with defined interfaces and standards (Silver, 2010). The philosophy of minimally controlled proliferation of alternative design approaches produces many alternative designs and commonality benefits. For example, consider a possible section of the human exploration architecture which is the transfer of propellant from Earth's surface to an on-orbit propellant depot. An open architecture would encourage many different vehicle designs competing to transfer propellant to the depot. The benefits would be largely from innovation and competition as different organizations competed to transfer fuel to the depot. There would be little commonality benefit. A commonality approach on the other hand would obtain its benefits from a single vehicle design sent repeatedly to the depot, meaning learning benefits and economies of scale in manufacturing and operation of the vehicle as well as higher proven reliability.

This does not mean that open architectures and commonality are an either / or choice for the whole of the exploration architecture. Rather, the architecture may need to be partitioned and a commonality approach applied to some sections and an open architecture applied to other sections. For example, a commonality approach could be used for the deep space infrastructure such as in-space propulsion and habitation modules, and an open architecture approach used for fuel, crew and cargo to LEO.

The effect of this observation on this thesis is that the system-level acquisition strategies evaluated for commonality effect in Chapter 5 may not be the most appropriate for all the systems in the architecture; rather, a commonality approach should be selected for those acquisitions where it makes sense.

Table 7: The interplay of commonality and other architecting strategies

	Modular Architecture	Interoperable Architecture	Open Architecture
Description	A modular architecture aims to design and build systems or sub-systems which can be used multiple times in the same or other products.	Interoperable architectures are designed to permit predictable interaction between different systems. In practice, systems are usually designed to be interoperable with multiple other systems forming a network.	Open architectures define interfaces and standards in order to allow wide participation in the achievement of an architecture (Silver 2010)
Interaction with commonality	Modularity encourages reuse by improving the ability to identify potential reuse and reducing the cost of actual reuse. Modularity is the essence of building-block commonality.	Some commonality between two systems helps to ensure interoperability, even though it is a non-necessary and insufficient condition for interoperability. In very general terms two systems with common interfaces or common protocols are less likely to cause interoperation difficulties than trying to interoperate two unique systems.	Open architectures allow different organizations to contribute their products to a system. Usually the commonality between these products is limited to that specified in the open architecture. The benefits of openness (especially for innovation) are predicated on organizations taking different approaches to their products. This means that it is largely incompatible with commonality.
Conclusion	Strongly complementary	Complementary	In tension

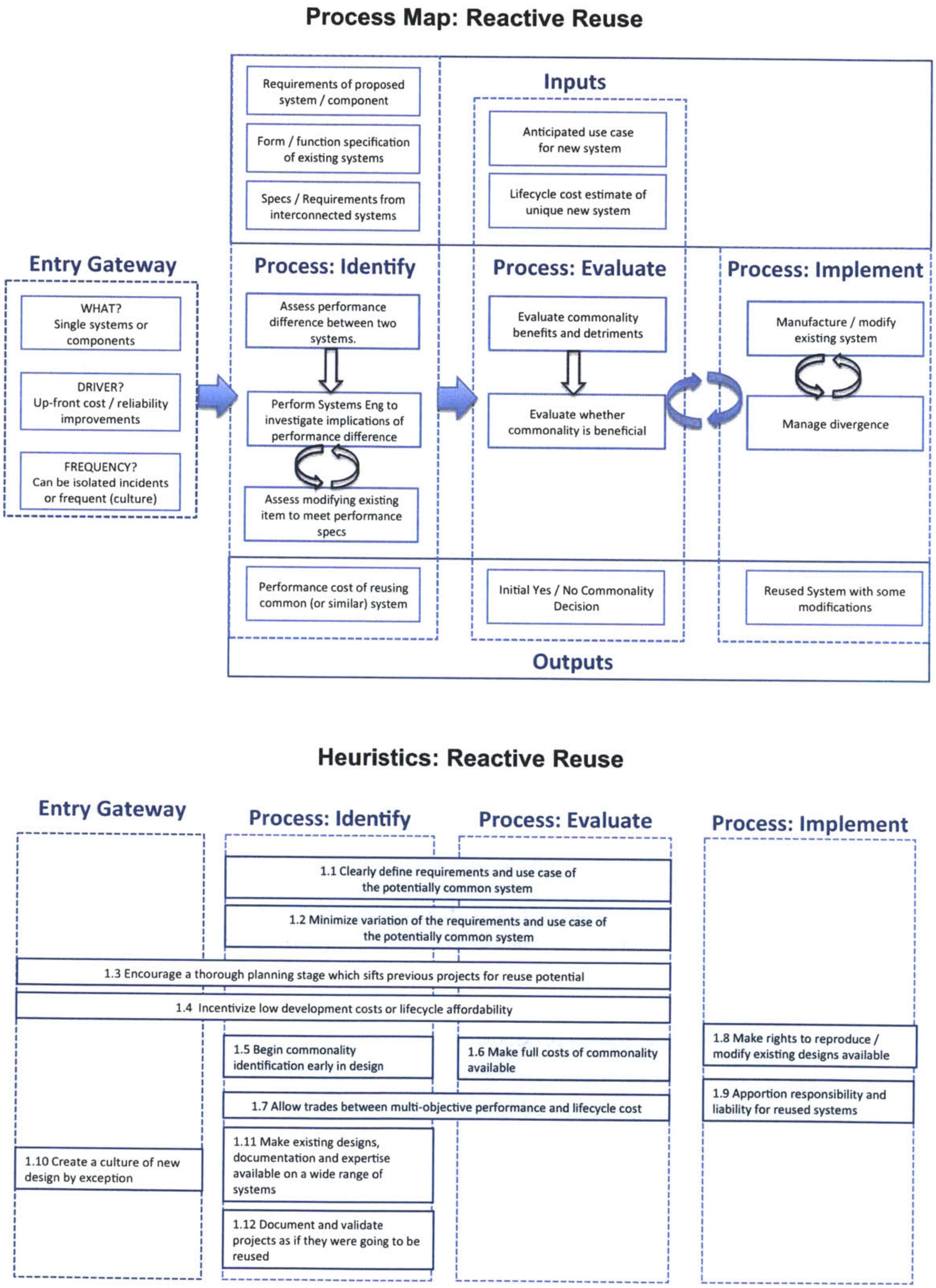
Developing Commonality Process Maps

The final part of the overview of commonality theory synthesizes the fieldwork undertaken for this thesis with that of Boas and Rhodes and the technical analysis by Hofstetter to produce a series of commonality process maps. The maps are shown in Figure 14, Figure 15 and Figure 16 for reactive reuse, common building block and widespread forward commonality strategies, respectively. The maps are accompanied by heuristics which capture best practice in gathering the inputs and performing the processes shown on the maps. The maps will be used in analyzing the commonality effectiveness of the acquisition. An acquisition strategy which leads to "good" performance on the process map, as defined by the heuristics, will score well for commonality effectiveness.

The process and heuristics are similar, but not the same, between the strategies for reactive reuse, common building block and wide-spread forward commonality. In the figures, the processes or heuristics which differ from the previous figure are marked in red outlines. Heuristics which continue through to the next figure substantially unchanged are shaded in light blue, those which are specific to the strategy being examined have no shading.

The process maps add an "entry gateway" to the identify, evaluate, implement framework of Rhodes. This is required because the types of projects which are appropriate to each process are different, and the entry gateway allows this to be specifically considered. It is also necessary because some heuristics are intended to encourage entry into the commonality process rather than any particular phase and the idea of an entry gateway permits bookkeeping of these heuristics.

Each commonality project is different but the process maps are intended to be general enough to capture the flow of almost all types of commonality. The straight arrows show progressions from step to step, and the circular arrows indicate iterations between processes.



1.1 Clearly define requirements and use case of the potentially common system

1.2 Minimize variation of the requirements and use case of the potentially common system

1.3 Encourage a thorough planning stage which sifts previous projects for reuse potential

1.4 Incentivize low development costs or lifecycle affordability

1.5 Begin commonality identification early in design

1.6 Make full costs of commonality available

1.7 Allow trades between multi-objective performance and lifecycle cost

1.8 Make rights to reproduce / modify existing designs available

1.9 Apportion responsibility and liability for reused systems

1.10 Create a culture of new design by exception

1.11 Make existing designs, documentation and expertise available on a wide range of systems

1.12 Document and validate projects as if they were going to be reused

Figure 14: Process map and heuristics for reactive reuse

Description of Reactive Reuse Process Map.

The process map for reactive reuse is shown in the upper half of Figure 14.

The entry gateway shows that reactive reuse processes usually act on single elements considered in isolation. In other words, a system or project development unilaterally decides to investigate previous or existing projects to obtain commonality benefits. The driver for this process is usually up-front benefits from reduced development cost, increased design confidence or improved reliability. Reactive reuse can be called upon regularly in a project, or infrequently, depending on the culture in the organization.

The first process is to identify opportunities for commonality. The inputs to this process are technical: an understanding of the form and function of existing elements which may be reused, the specifications or requirements of elements interconnected with the proposed elements, and an understanding of the requirements of the proposed elements.

The process itself is broken down into three steps.

1. The similarity in performance between existing elements and the potentially common element requirements is first examined. Both of the inputs are needed in making this comparison.
2. It is unlikely that a reused element will be perfect in terms of form and function, particularly for systems instead of simpler components. The effect of reusing an existing system on the proposed development as a whole must be considered. For example, if a potential reuse of a solar panel would deliver slightly less power than the requirements, can the power budget for interconnected systems be adjusted downward so that the performance is acceptable?
3. The final process step in identifying opportunities for reactive reuse is to assess whether the potentially reused element could be slightly modified to deliver performance closer to the requirements. For example, the solution might be to upgrade the solar cells from silicon to gallium arsenide, but retain all mechanical systems of the existing panel unchanged. It is likely some iteration between steps 2 and 3 will be required to reach an outcome which satisfies the technical requirements of the element as a whole.

The output of the identification process in reactive reuse is an assessment of the technical feasibility of reuse which usually identifies the performance cost of such reuse.

The performance cost of reuse is used in the evaluate phase, where the costs and benefits of the reuse are considered. The inputs to this phase are the use case (how the system is likely to be utilized in context of the broader architecture) and, as a comparator, the estimated lifecycle cost of developing the system without commonality.

The evaluate process is broken down into steps:

1. The advantages and disadvantages of the commonality are evaluated. This evaluation uses the performance cost assessed in the "identify" phase. It also requires the "use case" or conops for the new system, because factors like the projected number of systems produced and the production time period will affect the advantages and disadvantages.
2. The net benefit (or detriment) of commonality in the proposed system is compared with the likely outcome of unique development. In order to make this comparison, the estimate of the lifecycle cost of the system without reuse is required.

The output from the evaluate process is a decision as to whether it is economically sensible to proceed with a reuse strategy. Often there is uncertainty around future events which will impact the decision, so the evaluate process may be probabilistic (Rhodes 2010).

The final step in reactive reuse is to implement the commonality. Implementation is a two step process.

1. The common element is developed and manufactured, perhaps with some modification from the reused design. It may be manufactured by the original organization, or from its designs by a new company. It may even be reverse engineered.
2. Divergence is managed. As the development of the reused element progresses, management processes to minimize unacceptable divergence must be in place. Those management processes will need to reflect, and interact with, the development process. Therefore there is iteration between development and the management of divergence.

There is also iteration between the implementation of commonality and the evaluation process. As new information comes to hand during implementation, even a reactive reuse strategy should be continually evaluated in the light of any new information, and divergence allowed to occur if necessary.

The output of the implementation phase is a reused system, probably with some modifications to the original if it is a complex system.

Heuristics for best practice on reactive reuse

In addition to identifying the processes which lead to reactive reuse, previous work also identified heuristics for performing the processes well. The heuristics are summarized in the lower half of Figure 14. These heuristics are used in Chapter 5 to help assess whether an acquisition structure will allow the processes to be performed well.

Heuristic 1.1: Clearly define requirements and use case of the potentially common system

The requirements and use case are important inputs into the analysis of reactive reuse potential. If the requirements or use case are ill defined then there is additional uncertainty in the commonality analysis and the potential for divergence increases.

Heuristic 1.2: Minimize variation of the requirements and use case of the potentially common system

Changes in requirements or use case change the assumptions on which the analysis is undertaken. The changes will necessitate a new analysis if the project is still in the analysis stage. If development has begun, the element will either undergo divergence or commonality opportunities that could have been identified will go unimplemented.

Heuristic 1.3: "Encourage a thorough planning stage which sifts previous projects for reuse potential"

This heuristic is quoted from Boas. The identification and evaluation phases take time to undertake properly. More time on these phases increases the chance that if a favorable commonality opportunity exists it will be identified.

Heuristic 1.4: Incentivize low development costs or lifecycle affordability

There must be a reason to undertake the commonality process. In the case of reactive reuse, incentivizing low development costs is usually sufficient because reactive reuse delivers savings prior to operations. It is also possible to encourage reactive reuse by incentivizing lifecycle affordability more generally.

Heuristic 1.5: Begin commonality identification early in design

Rhodes emphasizes that commonality identification should begin early in design. This allows maximum flexibility in the system engineering aspect of the identification process. Trades can be made with other systems to increase the possibility of including a reused element in the architecture even if it does not exactly match the original specification.

Heuristic 1.6: Make full costs of commonality available

Rhodes found that design teams would better consider commonality if they were exposed to the full cost implications of commonality over the lifecycle of the product.

Heuristic 1.7: Allow trades between multi-objective performance and lifecycle cost

As shown above, the benefits and detriments of commonality span performance, schedule and cost. Often, but not always, commonality delivers cost savings at the expense of performance. Commonality is most likely to be beneficial in systems where performance is not an absolute requirement, but rather where the concept of value (benefit or performance at cost) is used to drive system choices.

Heuristic 1.8: Make rights to reproduce / modify existing designs available

The case studies examined by Rhodes and those examined in Chapter 4 of this thesis found that reactive reuse was stymied in some instances by legal barriers. Reactive reuse requires the right to reproduce or modify the existing designs identified as potentially common.

Heuristic 1.9: Apportion responsibility and liability for reused systems

The case studies in Chapter 4 demonstrated that the issue of liability for reused elements can reduce the willingness of organizations to reuse elements. The implementation of reactive reuse should address liability.

Heuristic 1.10: Create a culture of new design by exception

Boas found that there was a cultural dimension to commonality design. He suggested that organizations should aim to make commonality culturally embedded into the organization, with common design the rule, rather than the exception.

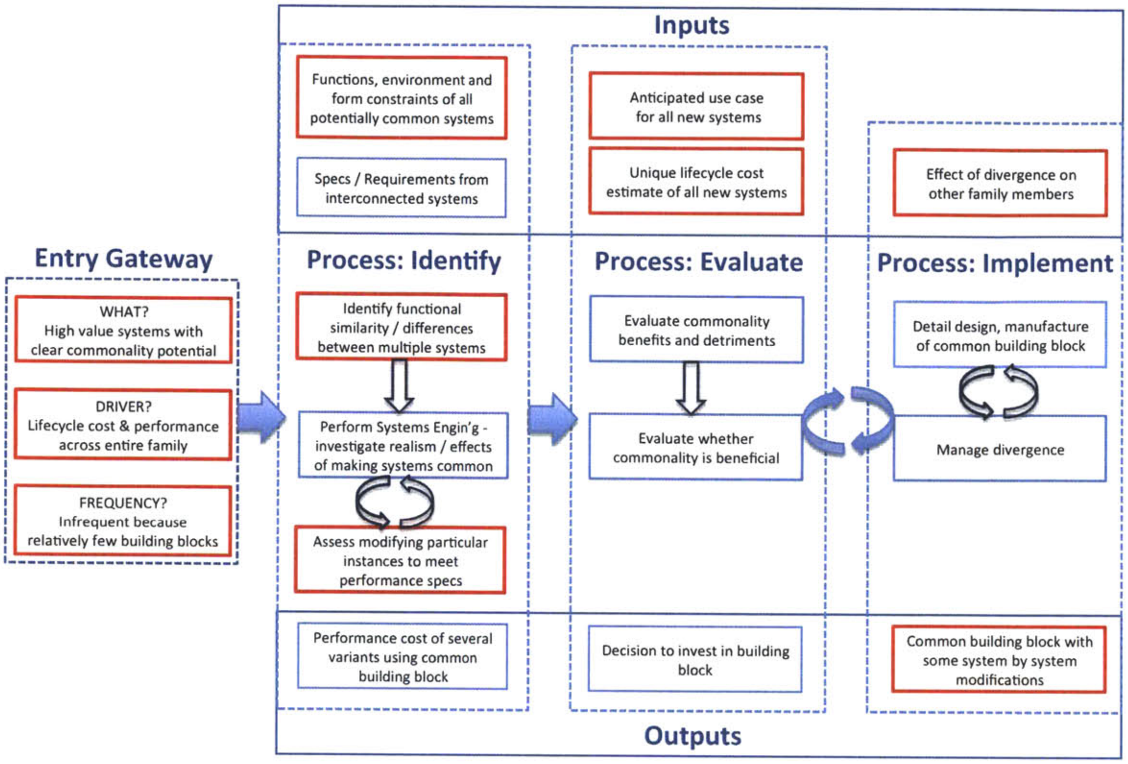
Heuristic 1.11: Make existing designs, documentation and expertise available on a wide range of systems

Reactive reuse depends on historical designs being available. Existing designs should be made as widely available as possible to increase the chances of an existing design appropriate for reuse being identified.

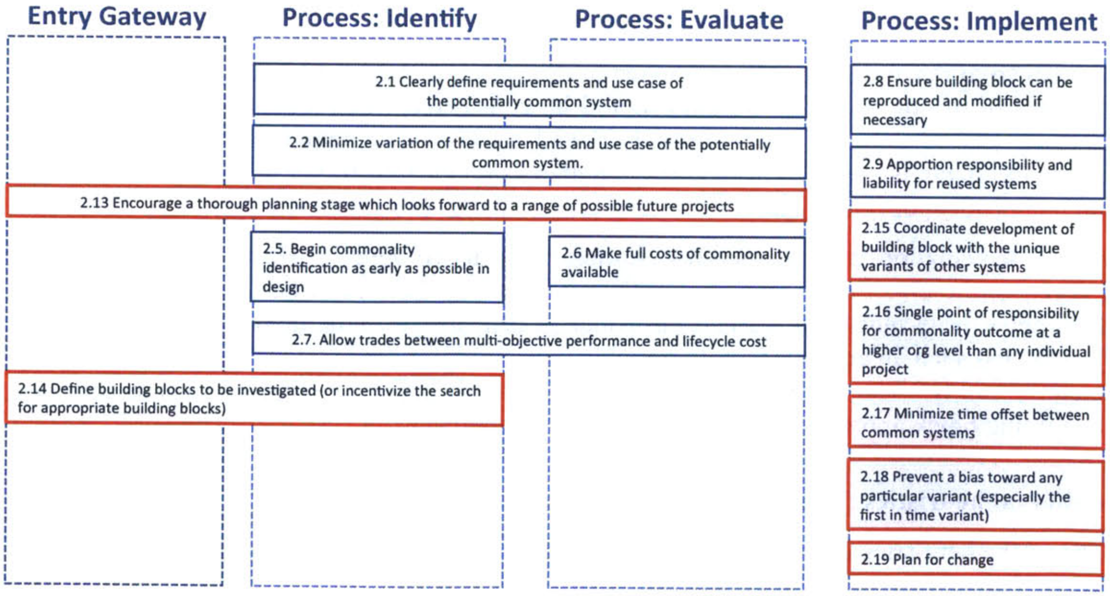
Heuristic 1.12: Document and validate projects as if they were going to be reused

Part of creating a culture of common design is creating the expectation that designs will be reused. Current designs should be packaged in such a way that they can be easily retrieved in future. Over time, this decreases the effort required to search existing designs and increases the likelihood and benefit of reactive reuse.

Process Map: Common Building Block



Heuristics: Common Building Block



2.1 Clearly define requirements and use case of the potentially common system

2.2 Minimize variation of the requirements and use case of the potentially common system.

2.13 Encourage a thorough planning stage which looks forward to a range of possible future projects

2.5. Begin commonality identification as early as possible in design

2.6 Make full costs of commonality available

2.7. Allow trades between multi-objective performance and lifecycle cost

2.14 Define building blocks to be investigated (or incentivize the search for appropriate building blocks)

2.8 Ensure building block can be reproduced and modified if necessary

2.9 Apportion responsibility and liability for reused systems

2.15 Coordinate development of building block with the unique variants of other systems

2.16 Single point of responsibility for commonality outcome at a higher org level than any individual project

2.17 Minimize time offset between common systems

2.18 Prevent a bias toward any particular variant (especially the first in time variant)

2.19 Plan for change

Figure 15: Process map and heuristics for common building block

Process map for a common building block strategy

A common building block strategy undergoes a similar process to reactive reuse except that the entry gateway is different, there are some process changes in the "identify" stage and the required inputs require more effort to collect. Figure 15 summarizes the process for a common building block strategy, with the changes from the reactive reuse structure outlined in red.

The building block strategy is the simpler of the strategies which look forward to build a family of products over time, and the entry gateway reflects this. Usually the products entering this process are high-value products and have clear commonality potential. The systems are driven to the process by lifecycle cost savings across the family (rather than the upfront benefit to a single product of reactive reuse). Relatively few elements per project enter this approach to commonality because the up-front commonality usually needs to be obvious for the projects to be singled out early enough for the commonality to be successful.

There are important changes to the identification process. The inputs to the process are now the requirements across *all* the variants which may use the building block. This is different to the reactive reuse approach which considered the requirements of a single product only. For example, in designing a building block engine for a launch vehicle family the thrust requirements for all vehicles would be required.

The first step of the identification process now needs to consider the difference in requirements of all the projects or elements which could use the building block, rather than the difference between projected requirements of a single element and known performance of an existing element. In practice, this probably means more iteration between the system engineering of the several variants to try to achieve a common solution.

The third step of the identification process also becomes less easily defined for the common building block structure. It is possible to make modifications to the building block to accommodate variants with unusual performance requirements. This effectively introduces another degree of freedom which can be adjusted to develop a technically feasible common solution. However, if too many variants need modification, unique design may be a better option.

Once a technically feasible solution is found, the commonality process moves to evaluate. Changes from reactive reuse are also made in this process. Under a building block approach, the use cases of *all* the potential variants should be considered when assessing the advantages and disadvantages of commonality. Similarly the lifecycle costs for unique development of *all* the potential variants is required to evaluate whether commonality in fact presents a better solution than independent development.

The implementation process is very similar to reactive reuse. However, when managing divergence, the effect of divergence on the family as a whole must be considered. Divergence which benefits an individual variant but which is detrimental to the family as a whole should be rejected, and such an analysis is only possible with full information (perhaps with uncertainty) on the entire family. The iterations between evaluation and implementation are just as important in the building block approach as in the reactive reuse approach.

Additional heuristics for a common building block strategy

Many of the heuristics for common building block design are the same as those for reactive reuse. Figure 15 shows the new heuristics for building block design in red outline. Heuristics shown in the figure without red outline are largely unchanged from the guidance for reactive reuse projects and are not explained again below.

Heuristic 2.13: Encourage a thorough planning stage which looks forward to a range of possible future projects

The thorough planning stage of reactive reuse must go further in the case of building block commonality. The planning must look forward to a range of possible future projects or elements, rather than concentrating on looking backward to historic projects. Future projects have additional uncertainties, making this process more difficult.

Heuristic 2.14: Define building blocks to be investigated (or incentivize the search for appropriate building blocks)

The search for building blocks has to be incentivized, particularly because the benefit to the first project to need the building block is likely to be minimal. The simplest, but not necessarily best, way of doing this is to require the investigation of building blocks on particular architectural elements like engines or avionics as an early and separate phase of development. An alternative is to incentivize the investigation of building block opportunities with bonuses or rewards.

Heuristic 2.15: Coordinate development of building block with the unique systems of other variants

The building block is developed as a new element which must interact with interfacing elements in several other projects. For example, a new launch vehicle engine must interact with the avionics and propellant tanks of each vehicle it powers. The development of the building block must be coordinated with the unique elements being developed for each variant. One way to ensure this occurs is to develop the building block first, but this may not be the best overall strategy.

Heuristic 2.16: Establish a single point of responsibility for commonality outcome at a higher organization level than any individual project

Rhodes emphasized the need for responsibility and accountability for commonality. He suggested that a single point of commonality responsibility at a level above any variant was the best way to achieve this.

Heuristic 2.17: Minimize time offset between development of two intended common systems

Boas suggested that as the time offset between common elements increases, the chance of successful commonality decreases. Therefore a successful building block strategy should not have a long time offset between two variants.

Heuristic 2.18: Prevent a bias toward any particular variant (especially the first in time variant)

Both Boas and Rhodes found that commonality could be compromised by an emphasis on the performance of a particular variant, usually the first in time variant. Good commonality practice avoids biasing the family towards the first in time variant simply because it is better defined and therefore easier to analyze.

Heuristic 2.19: Plan for change

Boas found that all commonality projects change in ways which are not predictable at the outset. Therefore a commonality project should have some allowances for changes to ensure that change does not send the project immediately into an expensive cycle of redesign.

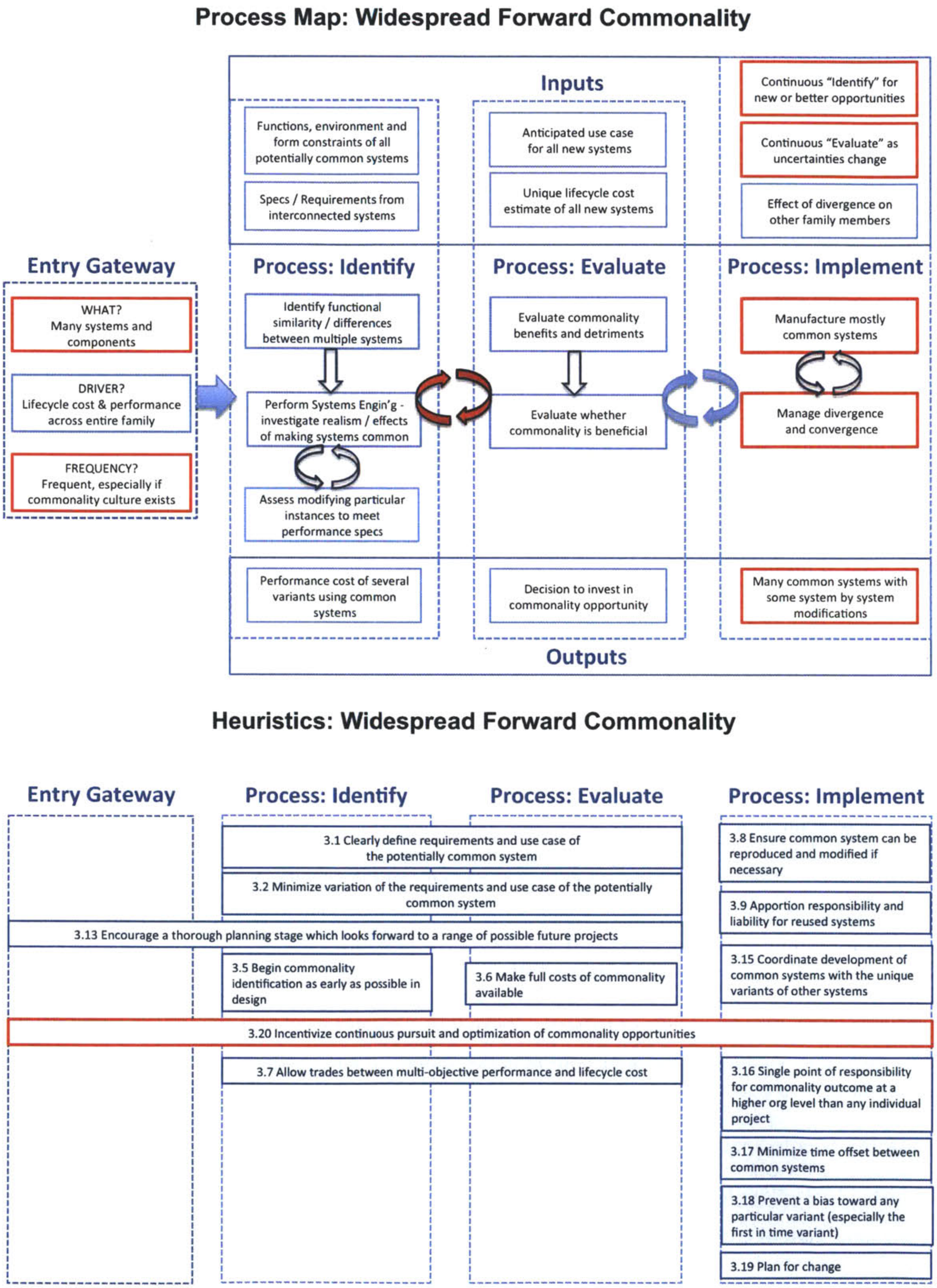


Figure 16: Process map and heuristics for widespread forward commonality

Process map for a widespread forward commonality strategy

The process for widespread forward commonality is broadly similar to developing common building blocks. Under widespread forward commonality, however, more elements pass through the commonality process, and the examination of divergence and commonality is more continuous. Figure 16 summarizes the widespread forward commonality strategy, with the changes from building block commonality outlined in red.

The increased number of elements entering the process can be seen in the changes to the entry gateway. More elements enter the widespread forward commonality assessment process. The range of elements which enter the process is also larger. Widespread forward commonality is likely to operate on the highest level of element where some commonality benefits can be gained, so components are likely to pass through widespread forward commonality in addition to complete systems. Contrast this with a building block strategy which usually focuses on complete systems because of their high value.

The initial identification and evaluation processes are very similar to the common building block processes. However, iteration has been added to the transition between identification and implementation. This indicates the increased fusion of the processes, so that evaluations indicating no commonality benefit are reexamined to see if additional benefit can be identified.

The idea of increased interaction is also shown in the additional inputs to the "implement" process. Ongoing identification and evaluation feed into the process of managing divergence. The manage divergence process also looks for opportunities to increase commonality over time. Although Boas showed that the general trend over time was towards divergence, he documented cases of new commonality opportunities being identified during the course of development. Constant management of these twin processes of divergence and convergence is a hallmark of widespread forward commonality.

Additional heuristic for widespread forward commonality

There is one additional heuristic for widespread forward commonality not present in the building block strategy.

Heuristic 3.20: Incentivize continuous pursuit and optimization of commonality opportunities

Widespread forward commonality requires continuous analysis of commonality. Identify, evaluate, implement cycles must be undertaken at regular intervals on a wide range of elements. For widespread forward commonality to occur, this process must be incentivized.

The preceding section has examined the existing literature and mined the case studies for best practice process and heuristics when developing for commonality. Using the process maps it is possible to be more precise in predicting which aspects of commonality an acquisition will do well at, and where it will perform poorly, a task which is undertaken in Chapter 5. Combined with the evaluation of NASA's acquisition task in section 2.1, there exists a good understanding of what a commonality acquisition strategy should do. However, understanding what *should* be done is not practical without an understanding of what *can* be done in terms of acquisition structuring. The following section will examine a range of acquisition strategies and contract approaches to provide an understanding of the available approaches.

2.3 TOOLS FOR CRAFTING ACQUISITION STRATEGIES

The previous section of this chapter described commonality best practice, however the question of improving commonality outcomes across multi-organization space architectures has not yet been answered. One final piece of background information is required before trying to answer that question. This section will provide it by describing the contractual tools available for crafting acquisition strategies.

Acquisition strategies can certainly affect the realization of commonality. The previous section showed how, among other concepts, developing commonality may increase the costs of systems early in development. The benefits of commonality may only be realized on a long-term view or from a perspective that encompasses the development efforts of multiple variants. Companies involved in developing systems for the exploration architecture may not have either of these perspectives. The acquisition strategy needs to either deliver these perspectives to the company, or deliver artificial incentives which produce the same results as would be achieved if the company was able to directly feel the benefits and detriments of commonality. In the absence of such incentives, companies would make decisions which optimized the variant they were producing at the expense of the commonality. In other words, in the absence of a considered acquisition strategy, undesirable divergence would occur.

Introduction and Overview

An acquisition strategy *"provides a business and technical management outline for planning, directing, and managing a project and obtaining products and services via contract*" (NASA, 2007a). The FAR encourages the creation of an acquisition strategy as early as possible in planning major projects: *"The program manager... shall develop an acquisition strategy tailored to the particular major system acquisition program"* (FAR section 34.004). In industry, acquisition strategy is often cast as the "make/buy" decision or subsumed into supply chain management. In this chapter, we will focus on cases where the government is the customer, and must work with both other government agencies and private-sector corporations because this most closely reflects the requirements of NASA. NASA may also be involved in architectures with foreign participation and it is worth noting that acquisition strategies can include foreign national governments and foreign-owned corporations.

Although media accounts of government acquisition focus most stridently on concepts like "fixed price" or "cost plus" payment, an acquisition strategy involves more than just considering how the contractor should be paid for its work. The acquisition strategy includes analysis of the broader sequencing and context of contract award in order to deliver a better result. None of the following examples consider payment structure, but all will affect the schedule, quality and price of the product:

- Using a series of yearly contracts instead of just a single total quantity contract to encourage more continuous competition.
- Splitting the technical deliverables into block upgrades to reduce technical risk.
- Awarding contracts to multiple companies to encourage competition.

In its simplest form, an acquisition strategy sets out which organizations build what, when, and for how much. In complex system development, allowances have to be made for the fact that the buyer often does not know the detail of what needs to be acquired, or how long it will take, or how much it *should* cost (an entirely different question to how much it would like it to cost). Therefore acquisition strategies must be more flexible than just setting out corporation, schedule and price. The tools of this flexibility are the subject of this chapter.

The US human exploration architecture – in whatever form it emerges from the post-Constellation political and technical debate – is a program that requires an acquisition strategy. In fact, the human exploration architecture is likely to require tiers of acquisition strategies. Some will dictate the overall approach to acquiring the necessary capability over timeframes of decades while others will be focused on delivering particular systems in shorter periods.

There is a fundamental difference between the single acquisition structure which is applied across the top level of the entire human exploration architecture, and the multiple strategies developed to acquire particular systems. This distinction is illustrated in Figure 17. In this thesis, the two tiers are called the "Program Acquisition Structure" and "System Acquisition Structures". Program Acquisition Structures control the program as a whole, and are chiefly concerned with the integration of projects into an interoperable whole. The Program Acquisition Structure connects the program to its projects and is shown in red in Figure 17. Only one Program Acquisition Structure can be used at a time across the human exploration architecture. On the other hand, there can be a range of System Acquisition Structures, shown in green in Figure 17. For example, the acquisition structure chosen for the avionics system on the lunar lander need not be the same as that for the avionics system on the launch vehicle, or that on the ECLS system on the lander. Note that the System Acquisition Structures need not be confined to the top level of systems in the acquisition, but can be used for any tier below the project level. Four possibilities for Program Acquisition Structures will first be examined below. Six possibilities for System Acquisition Structures will then be examined.

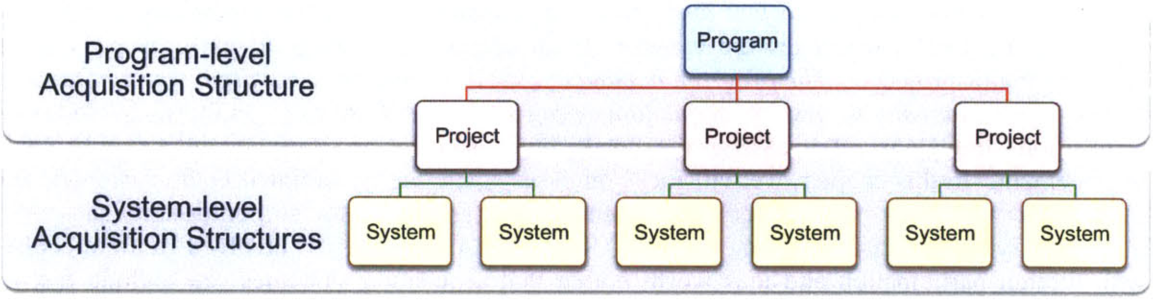


Figure 17: Two Tiers of Acquisition Structures

"Structure" refers to the network of contracts between the organizations developing elements of the Acquisition structure, regardless of the level at which those organizations operate. Essentially, the structure dictates "who is working for who". An acquisition strategy is more than just the contract structure, however. The contracts themselves contain important tools for shaping contractor behavior. For example, commonality incentives will be affected by the basis on which contractor payments are calculated. Barriers to later reuse will be lowered if the government receives the intellectual property developed by the contractor. After the examination of Program Acquisition Structures and System Acquisition Structures, this section will look at seven categories of contract terms which affect commonality, specifically:

- Payment structure: examines the payment and risk structure of the contract, including incentives and award fees.
- Contract deliverables: examines the systems or services which the contractor is required to deliver under the contract.
- Contract phasing: examines the points at which new contractors are permitted to bid for the work.

- Contract termination: examines the circumstances under which the contractor can have its work package terminated.
- Insight and oversight: examines the level of insight that NASA has into the activities of the contractor.
- Intellectual property: examines the intellectual property provisions of the contract.
- Socio-economic programs: examines the effect of additional FAR requirements dealing with socio-economic outcomes from government contracting.

Program Acquisition Structures

The analysis begins with the Program Acquisition structures, the highest level of acquisition structures. Four structures are proposed and discussed:

- **Multiple Primes:** the traditional approach where a separate prime contractor is responsible for each project and NASA undertakes system engineering and integration.
- **SETA structure:** NASA still contracts with a network of prime contractors is used but a separate organization takes on some of the system engineering and integration (the acronym for the organization's functions is SETA, standing either for Systems Engineering and Technical Assistance, or Scientific, Engineering, Technical and Analytical assistance, depending on the context).
- **Alliance structure:** NASA works jointly with a commercial organization and forms a separate board comprised of both NASA and contractor personnel to manage the acquisition.
- **TSPR structure:** NASA's responsibilities are reduced to those of a customer, and a commercial organization, known as a TSPR contractor which stands for Total System Performance Responsibility, performs all system engineering and integration program-wide.

The structures form a spectrum based on two variables, as shown in Figure 18. The first variable is the degree to which NASA is involved in system engineering, which distinguishes all structures except SETA and Alliance. The distinction between SETA and Alliance is whether the responsibilities for system engineering and integration are clearly delineated by contract (as they are in a SETA structure) or whether the responsibilities are shared (as they are in an Alliance structure).

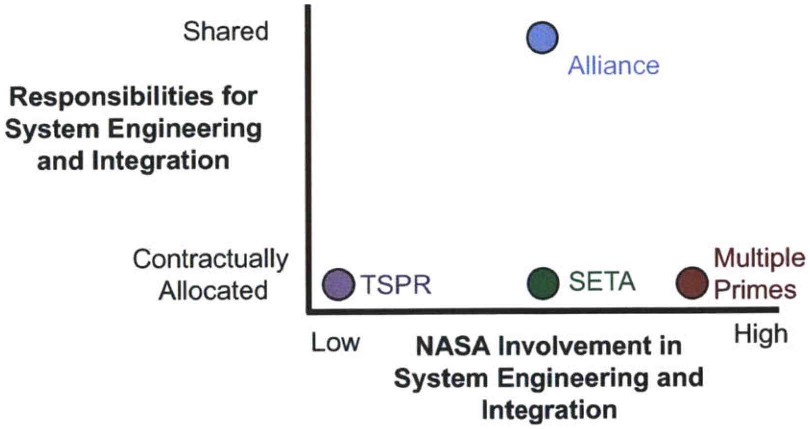


Figure 18: Spectrum of Program Acquisition Structures

Multiple Primes

The first Program-level structure to be examined is the "Multiple Primes" structure. In this structure, the government functions as the system integrator and system engineer, and apportions the development of systems between a number of contractors. The contractor still undertakes development of individual systems, but the government is more heavily involved in the system engineering tradeoffs and takes more responsibility for the final product.

An example of this structure at the Program level is the Apollo Program. Each project (for example the Command and Service Module, the Lunar Module and the launch vehicle stages) was under contract to a different prime contractor. NASA was responsible for overall system engineering and integration.

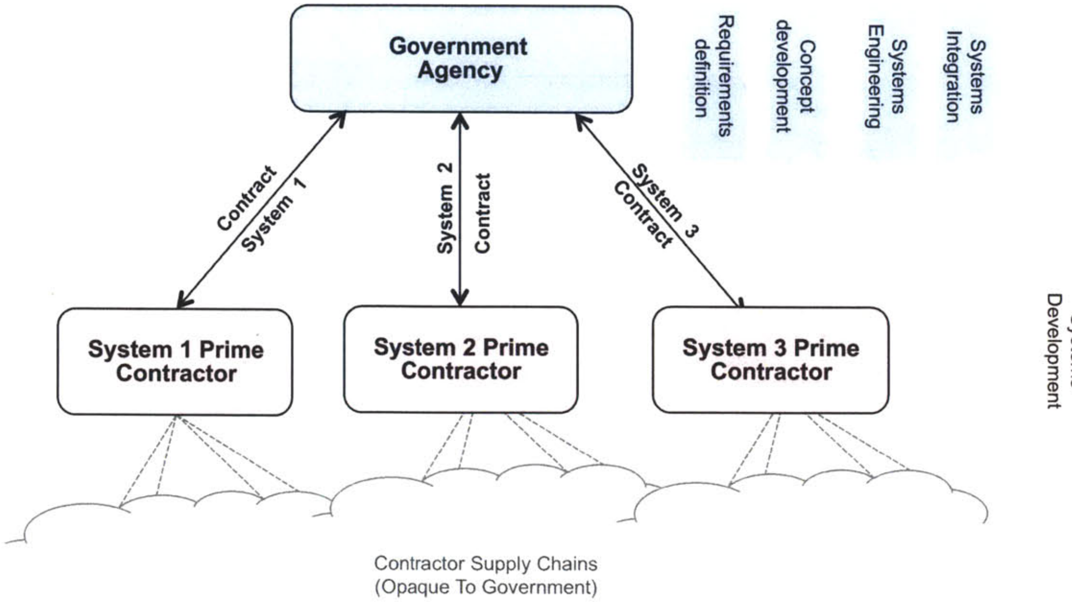


Figure 19: Multiple Prime Contractor Structure

Multiple Prime Contractor Structure	
Advantages	**Disadvantages**
Government has more insight into the project development and can respond more quickly and intelligently to difficulties	Government requires more in-house expertise to undertake systems engineering and systems integration
Government has more control over which contractors build which systems, allowing policy objectives to be realized and strengthening the long term force that rewards good performance on NASA contracts.	Creative and holistic concept solutions from industry may be more difficult to obtain because the scope of the design tasks given to each contractor are more limited

SETA

In some cases, the government may require additional system engineering and integration expertise. The government may use a system engineering integration contractor to work closely with NASA. Importantly, the government retains all contracts with the prime contractors for the projects, and the SETA contractor does not take on any development contracts, both of which distinguish this structure from the TSPR structure. The government may delegate much of its power under those contracts to the system integrator if the system integrator is to handle the day-to-day project management, but the system prime contractors remain contracted to the government.

NASA realized the need for system integration expertise on the Apollo program, although the system integration contract was not sufficiently widespread to be described as a program-wide SETA contract. After the Apollo 1 fire "*Webb arranged a contract under which Boeing would provide NASA with advice on integrating the spacecraft and the rocket*" (Bromberg, 1999, p. 71).

Under that contract, Boeing assisted in analyzing the "pogo" oscillations in the Saturn V and also performed *"sneak circuit analyses [which] it was felt all along...should be made, but personnel had not been available to do so."* (Bob Gilruth, quoted in Levine at p. 91)

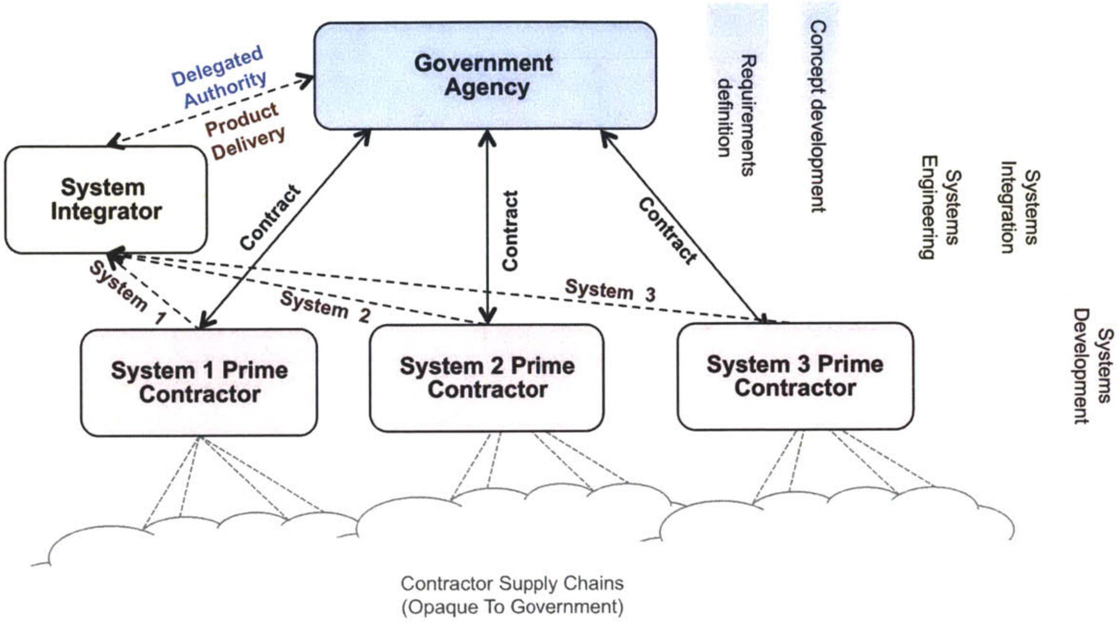


Figure 20: Commercial System Integrator

Commercial System Integrator Structure	
Advantages	**Disadvantages**
Government can draw on the expertise of the system integrator to complement its understanding of the system.	The system integrator adds an additional layer of management to the project. This increases the risk of duplication or omission of activities, and adds cost.
	Conflict of interest issues may arise which prohibit the system integrator from participating in any subcontracts. In complex system cases there may be a limited number of competent contractors and removing the system integrator from the competitive pool may be undesirable.

Alliance structure

Alliancing arrangements can be best thought of as a "joint venture" between the customer and the contractor. During the late 1990s and early 2000s they came into vogue for civil construction contracts, where they were seen as a new way of reducing risk in a litigious sector of engineering. Interestingly the contracts in many ways mimic strategies which have existed since the 1950s in government aerospace projects. For example, a cornerstone of alliancing contracts is the sharing in cost overruns and underruns which was a key incentive used in the early aerospace projects.

The advantage to re-examining alliancing contracts in light of their recent use on oil and gas projects and high visibility public sector projects is that there is now a broader base of experience to draw on when formulating the contract and a broader range of success stories for project participants to draw comfort from.

Each alliancing contract is adapted to its own environment, but there are some usual features:

- both contractor and customer share in project successes and failures. This is achieved by cost underrun and overrun and by monetizing performance parameters.
- the contractor is not liable for any poor or defective performance on the contract, including negligence, unless it reaches the standard of "wilful default" which essentially involves the contractor refusing to work or deliberately sabotaging the project
- project decisions are made by an alliance board comprised of contractor and customer representatives rather than by the customer

Alliances underpin the "Public Private Partnerships" (PPPs) for building government infrastructure which have enjoyed both positive and negative press over recent years. Initially seen as a panacea for over-budget, under-performing government programs, serious doubts were cast over their effectiveness, before the view moderated to one that acknowledged PPPs as effective in the right circumstances (International Association of Dredging Companies, 2008).

Fully-fledged PPPs have been used twice in the space sector, for the acquisition of satellite communications for the British Ministry of Defense and for the acquisition of the Galileo satellite (Bertran & Vidal, 2005). PPPs also appear to have been used on some Japanese space projects (Hashimoto, 2009). Other projects have been transitioned to PPPs at some stage in their development, for example, the outsourcing of the Space Shuttle operations to United Space Alliance, or the outsourcing of the operation and maintenance of the US evolved expendable launch vehicle (EELV) fleet to United Launch Alliance.

Still, although the PPP model has proved successful in civil projects in the United States, it does not seem to have transitioned well to military and aerospace projects. Rendon and Snider include no acknowledgement of PPPs in their 2008 book on Defense Acquisition projects, and the DAU Acquipedia focuses on PPPs only in the context of depot maintenance: *"Toward this end, DoD, with support from Congress, has emphasized the use of Public/Private Partnerships (PPP). Although partnering can be implemented in many areas and functions, the primary focus has been on depot activities... "* (Defense Acquisition University, 2011b).

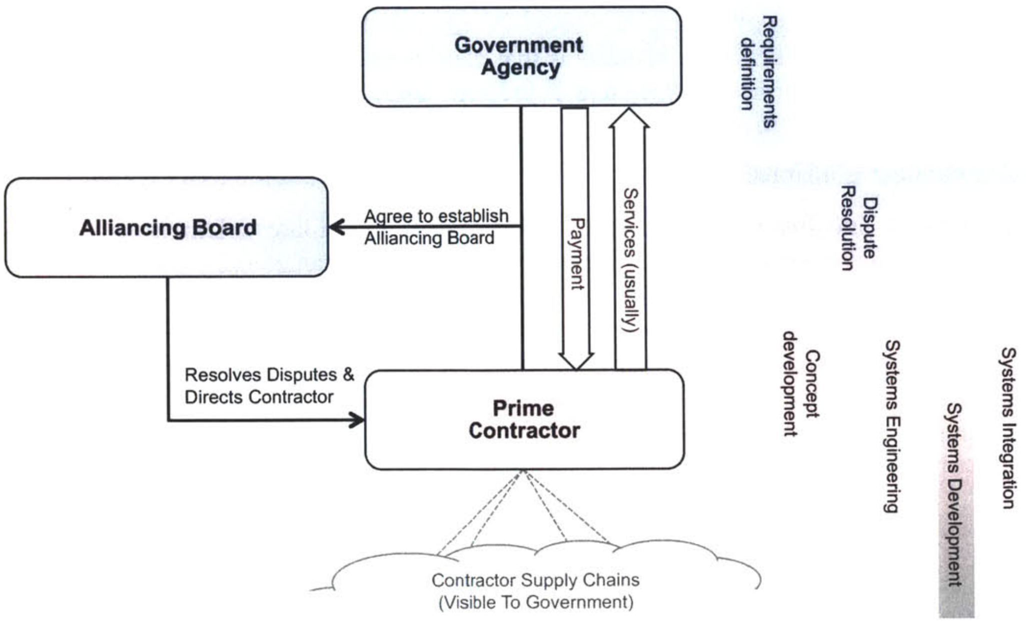


Figure 21: Alliancing structure

Alliancing Structure	
Advantages	**Disadvantages**
Better communication between customer and contractor	Additional effort must go into building the team at the outset of the program.
Less contractor *"capability, intellect, attention and energy"* (IADC, 2008) directed to exploiting the contract, or protecting itself under the contract, and more to delivering performance.	Government and contractor are left without the "protections" of normal contractual arrangement, leaving each exposed if there is a breakdown in trust.
The structure is more flexible to design changes which still achieve the initial goals.	Does not work well with more than two parties in the alliance because the alliancing board is too fragmented.
Customer and contractor both focused on longer term project success than with more traditional structures.	

TSPR Contract

TSPR stands for "Total System Performance Responsibility." Under this structure, shown in Figure 22, NASA acts as a pure customer, and requests a particular product from a contractor. The government contracts only with that contractor, which then subcontracts as appropriate. The TSPR contractor takes full responsibility for delivering the project. The terminology for this structure varies: TSPR is an Air Force acquisition term, while the Army describes the same structure as "Lead Systems Integrator."

The US contribution to the International Space Station closely resembled this structure, after the management approach was overhauled in the mid-1990s. The NASA budget request for 1996 summarized the new TSPR structure: *"an entirely new management approach has been implemented, in which a single contractor (Boeing) has been given total prime and integration* *responsibilities, with the previous prime contractors (McDonnell Douglas, Rocketdyne, and Boeing Huntsville) serving as first-tier subcontractors to Boeing"* (NASA, 1995).

A second example of this structure from DOD acquisition is the Future Combat System. Under this contract, the Army contracts only with Boeing, as the lead system integrator (LSI). The GAO described it as follows: *"The working relationship between the LSI and the Army is complex. The LSI is a traditional contractor in terms of developing a product for its customer, the Army, but also serves like a partner to the Army in management of the FCS program"* (Government Accountability Office, 2007b, p. 2). In the case of the FCS, the system integrator also helped the government define requirements and concept definition (Yakovac, 2008). Boeing's system integration team was prohibited from taking on subcontract work in that program (Government Accountability Office, 2007b, p. 33), and in that respect, the LSI contract in this instance takes one step closer to a SETA structure than a pure TSPR structure.

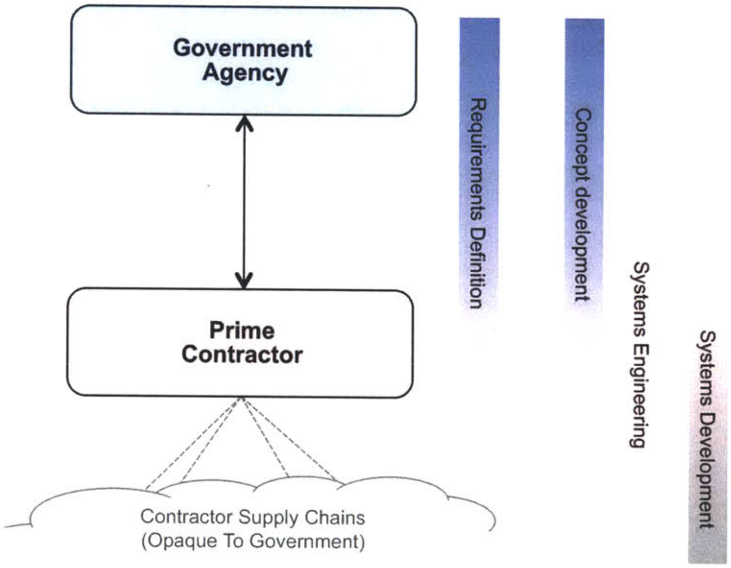


Figure 22: Prime contractor structure

The idea of a "prime" contractor who had responsibility for the system engineering and integration functions was developed in response to the difficult systems engineering tasks faced in ballistic missile production. Bromberg writes that in 1952 the Air Force introduced their "weapons system" contract where *"a prime contractor would be chosen and given wide responsibility for each system, including design, development, procurement of subsystems, and integrating systems into the final missile or plane"* (Bromberg, 1999, p. 25).

Generally, the contractor supply chains below the prime contractor are considered "opaque" to government, in that the government merely contracts with the prime which then subcontracts as it sees fit. The FAR controls the circumstances in which the prime contractor must obtain government consent to subcontract (FAR subpart 44.2). For NASA contracts, assuming the prime contractor has an "approved purchasing system," approval is only required to subcontracts specifically listed in the contract. It is likely that the prime contractor will have an approved purchasing system, as this is one of the barriers to entry that distinguish the large government prime contractors from similar organizations which operate only in the private sphere.

TSPR Program Acquisition Structure	
Advantages	**Disadvantages**
Single point of contact for the government simplifies contract management	Prime contractor may keep work for itself inefficiently instead of subcontracting (conflict of interest)
Theoretically, government only needs to know its needs, and does not require expertise in the project to be developed	In practice, government may not achieve good value for money if it does not understand the cost, schedule and performance interactions between its requirements
	High cost to switch prime contractor

System Acquisition Structures

System Acquisition Structures differ from Program Acquisition structures in that multiple System Acquisition Structures can be used across the architecture, in contrast with the single Program Acquisition Structure which must be used. Six System Acquisition Structures are considered:

- **Fully competitive:** The system is acquired by publishing the function-based system requirements and allowing all qualified bidders to submit proposals. The best bidder is chosen.
- **Joint venture:** A joint venture between two organizations is formed to build two or more systems, when, in the absence of the joint venture, the organizations would have built at least one each.
- **Directed contractor:** A contractor who has previously built a similar system within the architecture is selected without a competitive process.
- **Long-term supplier:** A contractor is chosen competitively at the outset of the acquisition of the exploration architecture as the sole supplier of a particular system element across the entire architecture.
- **Build-to-print:** A system is designed by the government,[5] and contractors are required to build that exact system from the detailed specifications provided. Also known as GFD ("**G**overnment **F**urnished **D**esign").
- **GFE:** A particular system is supplied directly to a contractor by the government[6] completely developed and requiring only integration. This is known as **G**overnment **F**urnished **E**quipment.

The System Acquisition Structures form a logical progression of government involvement, shown graphically in Figure 23. Government involvement increases to the right.

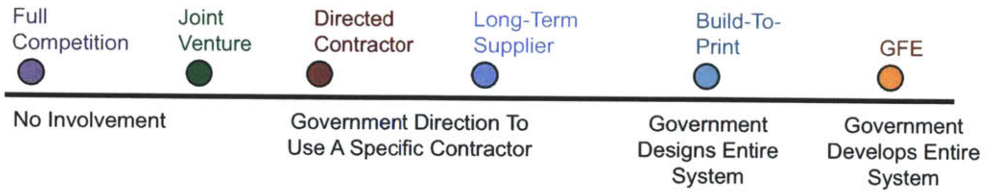


Figure 23: System Acquisition Structures lie along a spectrum of increasing Government involvement

Fully Competitive

Under the "Fully Competitive" System Acquisition Structure, the prime contractor for a particular project advertises its requirements for a particular system. It then receives a series of bids to build the system from different companies, and selects what it considers the "best" bid.

The chief advantage of this structure is that competitive forces between the bidders encourage each bidder to submit a bid which they believe has the best chance of winning.

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[5] In the case of both Build-to-Print and GFE, the most common circumstance in acquisition generally is that the design or system is supplied by the government. However, the design or system may be supplied by a contractor to a subcontractor lower in the acquisition hierarchy. The principles behind the acquisition strategy remain the same.

[6] See above note.

The structure is less effective when there is an oversupply of work in the market relative to the number of bidders because it reduces the incentive on each bidder to submit a bid which delivers the best value. The structure also works poorly at the opposite extreme, where bidders are desperate to obtain the work. In this case the practice of "buying-in" (submitting a low bid to obtain the work and making profit on later change requests) tends to lead to overly optimistic initial estimates and expensive or poor quality final systems.

The effort in preparing the proposal by the unsuccessful bidders also has a cost, which is effectively recouped through the unsuccessful bidders' profit or overhead rates on the projects which the bidder does win. On aerospace contracts the cost of proposal preparation is not insubstantial.[7]

Finally, the structure has been criticized for prioritizing the bidder with the lowest price over the bidder which offers the best value. Quality may suffer. Augustine cites the example of *"a military aviator [who] added to the "caution and warning" stickers that traditionally abound in the cockpits of modern rotary-wing aircraft, the following hand-lettered admonition: "Caution. This helicopter built by the lowest bidder.""* (Augustine, 1983, p. 222)

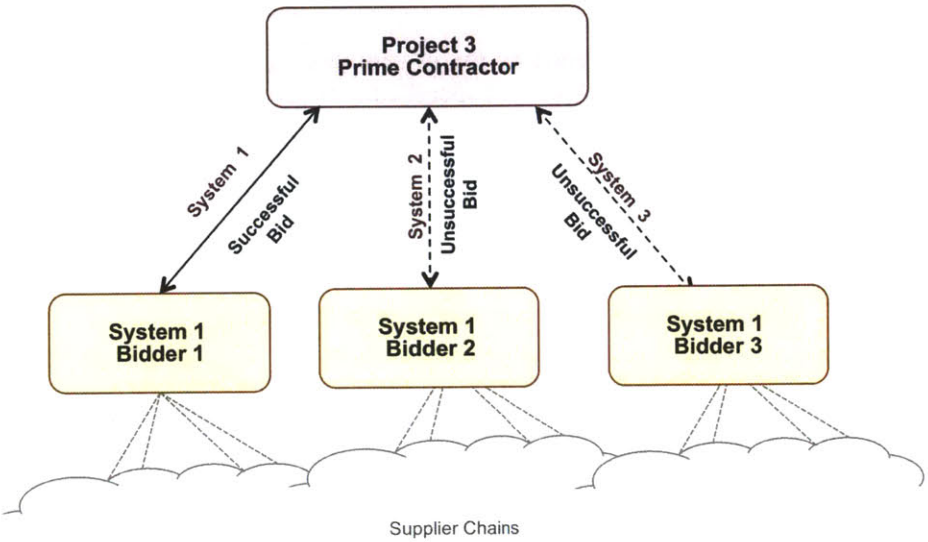

Figure 24: Fully Competitive System Acquisition Structure

A multiple-bidder structure has specific implications for commonality. The most important is the tendency for the system to be built by someone other than the incumbent (here, the organization which has most recently built a similar system for the government). New entrants win work under this structure due to their *inexperience*, which leads to overly optimistic cost estimates. Augustine's Law 33 neatly summarizes this point: *"Fools rush in where incumbents fear to bid."* When the government is the customer, this tendency has been exacerbated by the Truth in Negotiation Act (TINA), which requires in part that bidders disclose all they know about the system for which they are bidding (Rascusin, 1968). Given that experience usually teaches lessons about cost increases rather than decreases, an experienced bidder complying with TINA is likely to have a more costly bid than an inexperienced one. Therefore there is some incentive for the winner under this competitive bidding system to flip from one to the other. Such a transition between contractors makes it difficult to maintain commonality across systems.

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[7] Estimated in Augustine's Law Number 36: "The thickness of the proposal required to win a multimillion dollar contract is about one millimeter per million dollars…" (Augustine, 1983)

Fully Competitive Program Acquisition Structure	
Advantages	**Disadvantages**
General	
Fully competitive structure poses no regulatory difficulties.	Inefficiency of preparing unsuccessful bids.
If there are many participants in the market, there will be a downward pressure on prices and upward pressure on quality fed by a desire to win the contract.	If number of bidders is small relative to the amount of work then competitive forces are unlikely to be strong.
	Tendency for inexperienced bidders to win contracts because of their inexperience.
Commonality-specific	
	Emphasis on low-cost bidding disincentivizes lifecycle focus and commonality planning.
	Re-bidding each time a system is available for development does not encourage planning for future systems by early contractors, or continuity of knowledge from the previous system development.

Joint Ventures (and Mergers, Consortia and Collaborations)

Joint ventures are a device for fusing together the resources of two companies to exploit an opportunity which neither would be willing or able to tackle on its own, or to jointly serve a market that is too small for all competitors independently. Ingrao notes the increase in joint ventures in government contracting, attributing it to the fact that *"many larger government programs require expertise in so many different disciplines that very few defense contractors can meet all of these requirements…the use of joint ventures under some procurements has become a necessity"* (Ingrao, 1990, p. 399).

An example of the joint venture combining skills is the combination of expertise from Boeing and Bell on aircraft and rotorcraft expertise to develop the tilt-rotor V22 Osprey, defeating a consortium led by Sikorsky. Another example is GE and Rolls Royce working together on the alternate engine for the Joint Strike Fighter. An example of a joint venture created in response to shrinking markets occurred when Boeing and Lockheed joined their launch services divisions to create United Launch Alliance.

To show how joint ventures can contribute to commonality, consider Figure 25 and Figure 26. Figure 25 shows a Fully Competitive structure where System Contractor A and System Contractor B compete to win work on two different projects. System Contractor A wins on one project and System Contractor B wins on the second project. If instead a joint venture were formed which wins both contracts as shown in Figure 26, there is likely to be significantly greater visibility between the teams working on the system for Project 1 and the system for Project 2, and hence commonality will be easier to implement.

A similar scenario arises where the joint venture is formed to merge skills rather than to jointly capture the market. The resulting joint venture will have an advantage over lone companies in the market due to its depth or breadth of skills, and is more likely to win the contracts for both Project 1 and Project 2 than any single company would be. Once again, commonality will be easier to implement.

There are many shades of joint venture. On one end, the joint venture resembles a merger of two corporations into a single entity, as with ULA. On the other end, the joint venture can be merely a temporary cessation of hostilities brought about by a common enemy in the *"dog-eat-dog"* (Bromberg, 1999) world of the aerospace industry, such as the GE-Rolls Royce joint venture.

Legally, a joint venture may be either an "incorporated" joint ventures where a new company is formed, the shares in which are held only by the two joint venturers, or an "unincorporated" joint venture, which more closely resembles a partnership where both companies maintain their separate legal identity.

For the purposes of this structure, mergers (more permanent), consortia (less permanent) and collaborations (less permanent and more informal) are also considered as types of "joint venture". While this coarse clumping will cause lawyers to cringe, each effectively allows the two organizations to act in a manner closer to a single company than they could previously, though the degree to which this occurs depends heavily on the actual agreement between the two companies and the permanence of the arrangements. Specifically, these amalgamations:

- allow two organizations to draw on a common pool of skills
- increase visibility between the two organizations
- increase the interdependence of the organizations, so that if the joint venture, consortia or collaboration succeeds so do each of the organizations comprising it.
- present a façade of unity to an external customer, allowing that customer to reward, incentivize and instruct the company as a single entity

There are significant drawbacks to a joint venture from a contractor's viewpoint. The most significant are that liability for the actions of the other contractor is likely, and the joint venture may be subject to antitrust investigations (Ingrao, 1990).

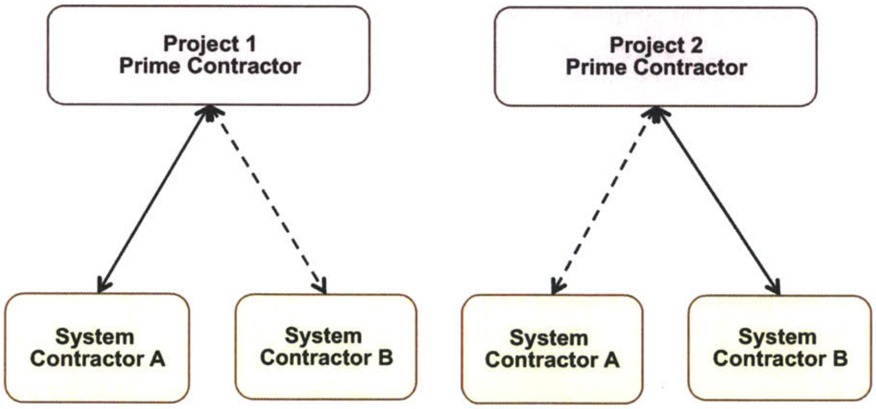

Figure 25: Fully Competitive Structure Prior To Joint Venture

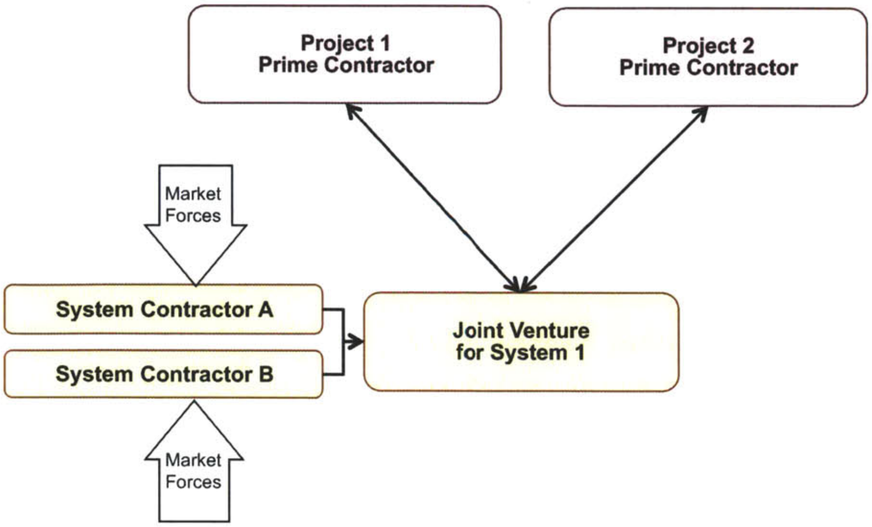

Figure 26: Joint Venture

Joint Venture System Acquisition Structure	
Advantages	**Disadvantages**
General	
In theory the customer does not have to concern itself with coordination of engineering designs, and knowledge transfer between the joint venturers	Joint ventures formed without substantial planning may increase the internal management overhead of an organization.
The joint venturers have a financial incentive to meet the requirements of the customer as efficiently as possible, using the expanded, shared resources at their disposal.	Organizational culture differences may interfere with the free transfer of information between the contractors
	Administrative and legal burden of establishing and maintaining a joint venture can be significant.
Commonality-specific	
Improved visibility between activities of two contractors lowers barriers to commonality identification.	

Directed Contractor

In some circumstances the government may select particular contractors to the project prime contractor. Although practitioners cautioned against this approach (see Chapter 3), it is historically a widespread practice in complex system engineering.

There are essentially two forms of directed contract, both shown in Figure 27. In one, the government contracts directly with the contractor, and in the other it is a requirement of the prime contract that a particular contractor is selected. The advantage of the first is that it is easier for the government to tender for that subcontract under the general FAR principles of *"competition...fairness and openness"*, however the disadvantage is that government takes on the burden of managing the contract. The advantage of the second is that it more accurately reflects the role which the contractor should play, on the other hand the prime contractor may find it difficult to exert strong control over the contractor because the contractor is in a protected position by being specifically nominated.

Relevantly, the directed contractor structure is often used to improve commonality across systems. An historical example is the use of subcontractors on the Apollo Lunar Module:

> *"NASA also disagreed with our choice of subcontractors for the environmental control system and the fuel cells. Our competitive selections had been very close, but in both cases we had selected another company over the existing supplier for the command and service modules. (We chose Pratt and Whitney for ECS and Hamilton Standard for fuel cells, the reverse of the CSM lineup.) NASA asked us to update the competition for the two top ranking companies, adding a requirement to maximize commonality with CSM equipment...we obtained revised bids from the subcontractors involved and changed our selections to the CSM suppliers of these systems."* (Kelly, 2001, pp. 43 - 44)

A similar approach was used more recently on the Army's future combat system:

> *"the noncompetitive selection of General Dynamics and United Defense as the manned ground vehicle integrating team...as these corporations were the providers of all the Army's current inventory of manned combat platforms, government management made the decision to maintain that portion of the [industrial] base."* (Yakovac, 2008)

NASA has also used the directed contractor approach to spread contracts around the industrial base. This improves public and congressional support for NASA and may also contribute to a more diverse supplier base, both of which are important longer term goals for NASA. The political reality of this approach was obvious early. In September 1961 *"the lore was that NASA would not give more than one major contract to any single firm. ... This would help ensure a cadre of capable firms for future contracts, and also build political support for its expanding space efforts"* (Bromberg, 1999).

On the shuttle program for example, George Low insisted on North American Rockwell (which won the orbiter) subcontracting *"to ensure that at least some of the money would be passed through to the losers"* . He wrote *"our procurement regulations permit this kind of sole source subcontracting"* (Bromberg, 1999). Eventually, Grumman won the wing, General Dynamics-Convair the fuselage, McDonnell Douglas the Orbital Maneuvering system, Fairchild the vertical tail fin, Martin Marietta the external tank and Thiokol the SRBs. Northrop and Boeing were the only two large aerospace firms to miss significant initial contracts on the Shuttle.

Note that NASA has a right to require it give consent to any subcontracts (clause 44.2 of the FAR), which it could use to narrow the field of potential subcontractors and approach a directed contractor relationship without necessarily specifying a particular contractor.

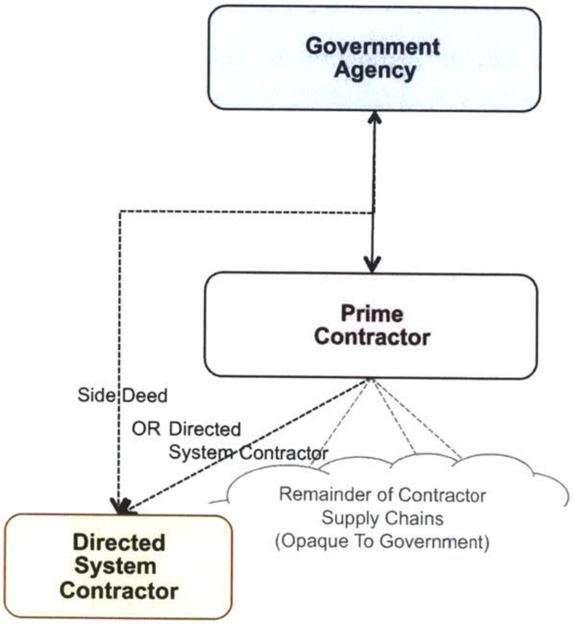

Figure 27: Directed sub-contractor structure

Directed Subcontractor Structure	
Advantages	**Disadvantages**
General	
Allows the agency to disperse subcontractor tasks to best meet non-engineering goals of the agency such as ensuring wide Congressional support.	There is an unclear division of responsibility for and management of the directed subcontractor's work, which may lead to project management difficulties.
Allows the agency to mandate particular pieces of work as subcontracted in circumstances where it is obvious that the prime contractor is not best suited to carry out this work, but may nevertheless be tempted to do so to maximize revenue.	In some cases directing particular subcontractors in the prime contract may appear contrary to the spirit if not the letter of the FAR and attract negative press coverage.
	The prime contractor may have a better working relationship with other subcontractors in the same area, and so learning to work with the directed subcontractor introduces inefficiencies.
	Using an existing contractor may reduce the chance of finding innovative system designs compared with a fully competitive structure.
Commonality-specific	
Choosing the same contractor is a simple way to give the contractor insight into previous designs.	
Reduces intellectual property and liability concerns associated with reuse (discussed further in Chapters 3 and 4).	

Long-term Supplier

The long-term supplier structure for system acquisition competitively selects a particular contractor as the supplier of a certain system *across the entire architecture*. Figure 28 shows this structure underpinning a Multiple Prime Program Acquisition Structure, but it could be equally used with other Program Acquisition Structures. Under this structure, it is mandatory for each of the prime contractors to use the long term supplier for a particular system.

The closest example to this type of system appears to be specialization among the member states of the European Space Agency (ESA). For example, ESA's pressurized modules are almost all built by Italian firm Thales-Alenia, and interviewees mentioned several other areas of specialization. However, this specialization appears to be more a matter of practice than an official policy of ESA. The official policy is still to create and increased specialization is mentioned as a possible area of future improvement: *"[there is currently] limited specialisation among suppliers of subsystems"* (European Space Agency, 2007).

The point which distinguishes a long-term supplier from a directed subcontractor is that the long-term supplier is a forward looking arrangement which extends across the entire architecture even if the more distant projects have not yet been awarded a prime contractor. The directed subcontractor in contrast is an arrangement which occurs project-by-project, and there is no assurance from the contractor's point of view that they will be chosen for subsequent projects.

A long-term supplier arrangement places the supplier into a strong monopoly position so the contract will require some mechanisms for removing the supplier, for example if cost growth is too rapid or if quality slips. Removing the supplier, though, undermines the whole principle of supplier continuity across the architecture and approaches a simple directed contractor structure. Therefore the strength of contractor tenure needs to be carefully considered.

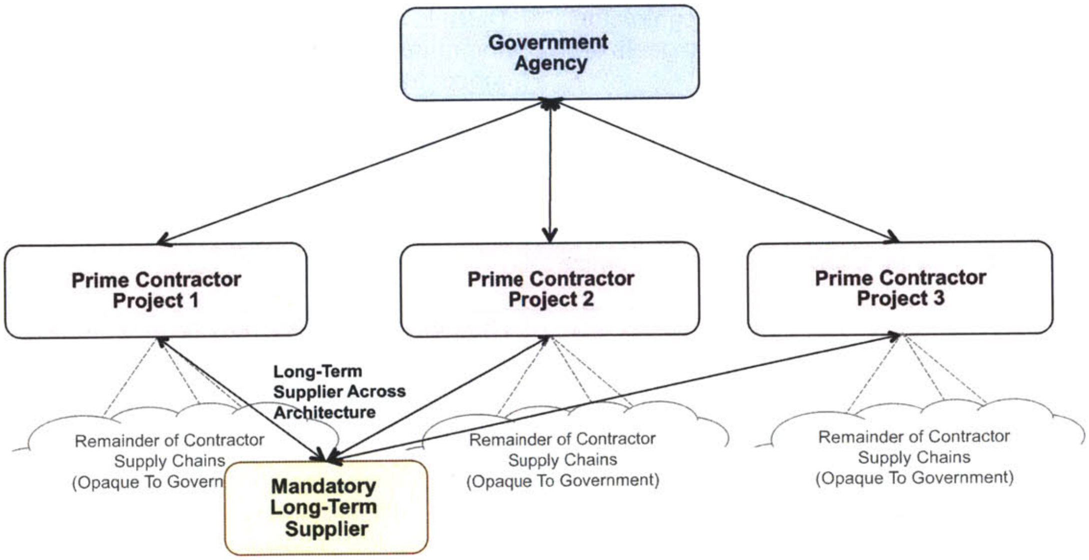

Figure 28: Long-Term Supplier System Acquisition Structure

Long-Term Supplier System Acquisition Structure	
Advantages	**Disadvantages**
General	
Choosing the same contractor is an important step towards enabling commonality with previous systems, and allowing the contractor to plan commonality with future systems.	There is an unclear division of responsibility for and management of the supplier's work, which may lead to project management difficulties.
Allows the agency to mandate particular pieces of work as subcontracted in circumstances where it is obvious that the prime contractor is not best suited to carry out this work, but may nevertheless be tempted to do so to maximize revenue.	Sole-sourcing a particular system over a time period of a decade or more presents significant regulatory challenges. It also presents price challenges if the supplier exploits its monopoly position
	The prime contractors may have a better working relationship with other subcontractors in the same area, and so learning to work with the supplier introduces inefficiencies. Equally, the supplier may work better with some prime contractors than others.
	The use of a single supplier reduces the industrial base making the provision of spare parts difficult if the original supplier should cease production.
	The use of a single supplier reduces the national dispersion of contracts, hampering efforts to gather broad Congressional support.
Commonality-specific	
Contractor can invest in commonality for future systems which it knows it is likely to develop.	

Build-to-Print

A Build-to-Print system acquisition structure, shown in Figure 29, occurs when all of the design is undertaken at a higher level in the acquisition structure, and the contractor responsible for the system need only build the system to the specifications provided. This approach uses specifications of form, rather than the more common practice of specifications of function.

Some of the benefits of commonality are lost, because two separate contractors (labeled C and D) need to integrate and manufacture the common systems (labeled 1A and 1B). Economies of scale and learning benefits are not realized to their fullest extent with this method. However, the philosophy is that the government customer will receive two identical systems at the conclusion of the acquisition and can realize recurring engineering savings during the operations phase, without asking contractors to work together with their competitors on design.

The feasibility of this approach depends heavily on how well finalized the technical details of the potentially common system are. If there is any development work required on the common system, divergence is certain to occur, and very likely this will occur in different ways under the two contractors. The final products will not be common and some of the benefits of commonality will be lost. To develop common products under this structure requires either:

1. Preventing divergence occurring, meaning minimal development work and short manufacturing timeframes; or
2. Managing the divergence so that the end products from each corporation remain common, meaning extensive change control and close co-operation through development.

Further casting doubt on the workability of fully specifying form to obtain commonality across two contractors, it is questionable if the form of the design could be fully specified in advance for most space systems. The most egregious example of this difficulty was the lunar lander contract. Tom Kelly describes the lunar module selection process:

"NASA considered both the mission planning and technical requirements too uncertain to buy a proposed design... the RFP was more like a graduate examination in an aerospace engineering course than a typical government procurement specification...

1. *Discuss the flight mechanics and other considerations of near-Moon trajectories*
2. *Describe your approach to the design of the following LM systems...*
3. *To what extent do you consider backup methods of control and guidance necessary?..."*

(Kelly, 2001, p. 28)

It is unlikely that NASA will be on a learning curve as steep as that in the early years of the 1960s again, but Kelly's "graduate exam" clearly shows that it is not always possible to specify the form of space systems exactly at the time contracts are opened for tender.

However, specifying function in the same situation would probably be even worse from the perspective of commonality. The benefits of commonality stem from common form, and specifying common functionality is unlikely to result in common form.

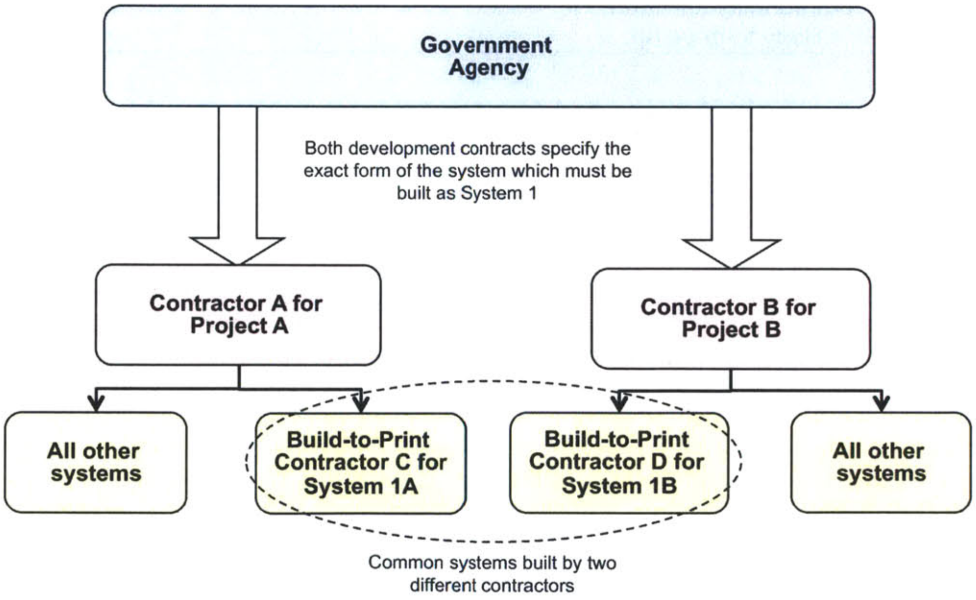

Figure 29: Build-To-Print System Acquisition Structure

Built-to-Print System Acquisition Structure	
Advantages	**Disadvantages**
General	
No regulatory obstacles.	System design must be finalized before contractor begins work.
Lower risk for contractors, hence lower margins and / or increased willingness to accept fixed price contract structures.	Government must understand the system and its requirements well enough to design it.
	Changes are expensive and difficult.
Commonality-specific	
Develops system-level commonality without requiring competitors to share information.	Copes poorly with any divergence.
	Commonality benefits are only in the operating phase.

Government Furnished Equipment

Government Furnished Equipment (GFE) takes the idea of specification of form one step further. In a GFE System Acquisition Structure, the developed system itself is supplied at the program level to all projects which require it. The GFE structure is shown in Figure 30.

The contractor need only interface with the GFE, and is not involved with its development at all. The GFE may be developed in-house by the government or supplied to the government by a separate contractor. This is still a requirement of form on the systems which must use it. However, the full form of the GFE system need not be known at the time the contracts for the variants are written, only the relevant interfaces and an envelope in terms of key design parameters like mass, volume and power draw. Further, the organization developing the GFE can have the requirements of the GFE specified in functional, rather than formal, terms. This avoids the rigidity of specifications of form and increases the design space which can be considered. The common system will be developed by a single organization, which increases the commonality benefits during the design and development phase, and removes the need for rigid change control between the two contractors to maintain commonality. One drawback is that the GFE contractor is unlikely to have full insight into the final requirements of both systems, and therefore the GFE may not be as well suited to the particular application.

However, NASA's previous experience, as embodied in the NASA supplement to the Federal Acquisition Regulations, appears to take a negative view of GFE:

> *"1845.102-70 NASA policy.*
>
> *Government property shall not be provided to contractors unless all other alternatives are not feasible. The decision to provide Government property to contractors (whether Government-furnished or contractor-acquired) shall be made only after careful consideration of all relevant factors. Among these factors are the following:*
>
> *(a) Providing Government property to contractors increases the Government's administrative burden and requires recordkeeping and personnel.*
>
> *(b) Providing property may dilute the contractor's overall responsibility and weaken guarantees, end-item delivery requirements, and other contract terms.*

> *(c) Providing property may make NASA responsible for delays in that the Agency assumes responsibility for scheduling delivery of the property."*

Supplying GFE is also, effectively, a specification of form on the organizations which will integrate the GFE and therefore limits the design freedom from the perspective of the final product. For this reason specifications of function are preferred. The FAR recognizes this when, in its regulations on the acquisition of major systems, it states: *"Agencies acquiring major systems shall: (1) Express...agency needs and major system acquisition program objectives in terms of the agency's mission and not in terms of specified systems to satisfy needs."* (FAR section 34.002) Often the contract goes further and requires that the contract not limit the ability of the contractor to propose new ways of achieving the goals, as when the RFP should *"clearly state that each offeror is free to propose its own technical approach, main design features, subsystems, and alternatives to schedule, cost, and capability goals."* (FAR section 34.005-2(b)(5))

An additional drawback of GFE is that the only way to change the commonality solution is to change the requirements themselves. Although frequently done, requirements change once the contract has been signed is damaging to project costs and schedules. Therefore this method of specifying commonality does not allow for flexible modification of the common systems which is often helpful in managing divergence. If the solution specified in the requirements is shown to be unworkable for one system, the two open options are less than satisfactory: to allow the systems to diverge, or to modify the contract of the still-compliant system to bring it into line with any design changes.

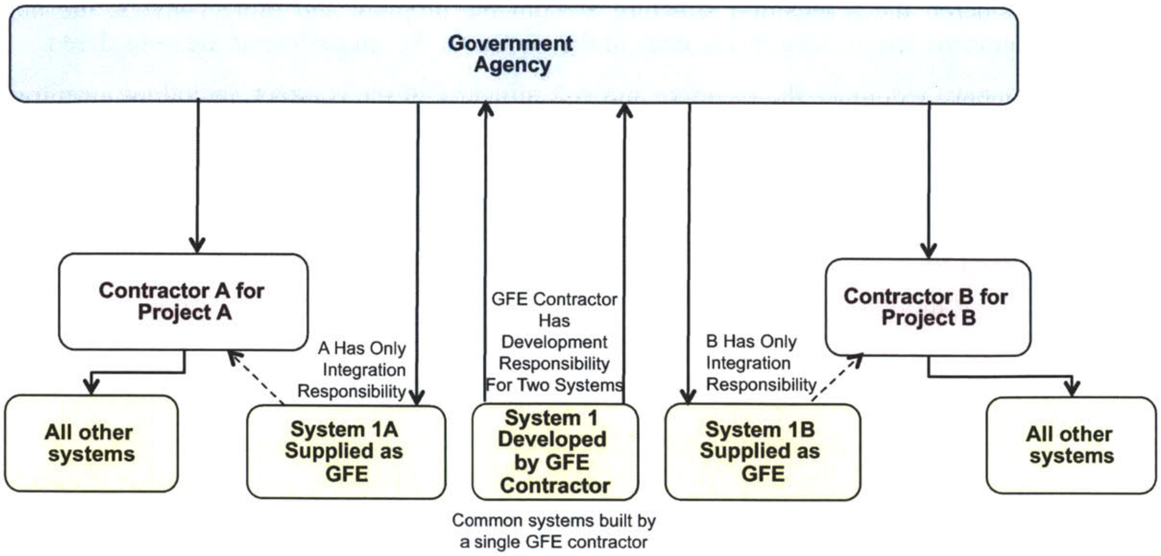

Figure 30: GFE as a System Acquisition Structure

GFE System Acquisition Structure	
Advantages	**Disadvantages**
General	
Reduces duplication of effort in developing systems compared to fully competing the system each time.	GFE imposes oversight responsibilities on government, which it has not traditionally performed well and is reluctant to assume.
	Requires coordination in interfaces and in system engineering to ensure GFE will integrate successfully and perform properly.
Commonality-specific	
Captures most of the lifecycle advantages as there is a single designer, manufacturer and operator (but not a single integrator, perhaps leading to some loss of benefit in testing and commissioning compared to the case where a single entity controls the entire development cycle).	Requires strong high-level commonality management to prevent projects requesting excessive variation in their items of GFE.
	Cumbersome to manage divergence across organizational boundaries.

Contract Terms

Having considered the acquisition structure at both the program and project levels, the next consideration is the terms contained in each of the contracts. Seven categories are considered.

- Payment: examines the payment and risk structure of the contract, including incentives and award fees.
- Contract deliverables: examines the systems or services which the contractor is required to deliver under the contract.
- Contract phasing: examines the points at which new contractors are permitted to bid for the work.
- Contract termination: examines the circumstances under which the contractor can have its work package terminated.
- Insight and oversight: examines the level of insight that NASA has into the activities of the contractor.
- Intellectual property: examines the intellectual property provisions of the contract.
- Socio-economic programs: examines the effect of additional FAR requirements dealing with socio-economic outcomes from government contracting.

Payment

The first category of contract terms concerns the way in which payment to the contractor is tied to the contractor's performance under the contract. This is perhaps the most important tool, because the payment to the contractor is a powerful behavioral incentive.

Payment is so intrinsic to the contract that the "type" of contract has become synonymous with the way the contract pays the contractor for their services and to the risk the contractor assumes in providing those services: *"the contract type defines the expectations, obligations, incentives, and rewards for both Government and contractor during an acquisition"* ("Contract Type" in (Defense Acquisition University, 2011b)). Part 16.101 of the Federal Acquisition Regulations describes the sweep of contract types:

> *"The specific contract types range from firm-fixed-price, in which the contractor has full responsibility for the performance costs and resulting profit (or loss), to cost-plus-fixed-fee, in which the contractor has minimal responsibility for the performance costs and the negotiated fee (profit) is fixed. In between are the various incentive contracts, in which the contractor's responsibility for the performance costs and the profit or fee incentives offered are tailored to the uncertainties involved in contract performance."*

This section will consider each of the contract types in detail. There is much scope for tailoring acquisition strategies using these techniques. However, the point to be borne in mind at the outset is that no finessing of the contract type is effective without a good understanding of the costs and risks involved with the project; that is, without an informed customer who understands the system trades likely to be made in development. The general rule is that the simpler the contract, the better, and more complicated payment structures should only be added when there is a clear contractor behavior which the payment aims to incentivize or disincentivize.

Table 8 sets out the contract types which will be considered in this section. The cost basis of the contract must be either cost-plus or fixed price. Then any or all of cost sharing, incentives, indexing or price redetermination can be layered on top of the cost basis to arrive at a mutually acceptable contract.

The overriding principle behind the range of types of development contracts is that development carries uncertainty, which translates to risk. Corporations taking higher risks require higher possible rewards in order to undertake those risks. The contract types should be viewed as tools for balancing the risk and reward between the government and the contractor. If the government wishes development projects with significant uncertainty to be developed, it must either shoulder some of the risk itself or be prepared to pay high profits to the corporation which takes those risks.

It should be noted that the presentation of the contract types in Table 8 is simplified. There are several types of price redetermination presented in the FAR, as well as constraints on which types of incentives are allowable. Additionally, there are a number of contract types not presented in Table 8 which are allowable under the FAR. Generally these would be used to fund research activities for small total cost. These contract types are minor contributors to the overall cost of NASA's exploration architecture and are thus ignored for simplicity. The subtleties of architecting an acquisition strategy which fits the letter of the FAR are not trivial, however this appears to be a matter of finessing the form of the contract, rather than its substance, and therefore Table 8 is an adequate summary of the tools available. Chapters 3 and 4 expand on how these contract types work in practice through interviews with practitioners.

The phase of development also has an effect on the likely contract type. As contracts move forward in the development cycle from the design phase to the manufacturing phase, there is less technical uncertainty implicit in the contract requirements. Accordingly, in the manufacturing phase contractors are more willing to accept development risk and contracts are more likely to be for fixed price. Fixed price manufacturing contracts are also likely to contain price-volume curves to account for the different costs of different levels of government demand and remove what could be broadly termed "market risk".

It appears to be possible for one contract to contain multiple contract types. For example, Firm Fixed Price could be used for some well defined elements, while cost plus contracts could be used for other elements in a single piece of equipment. Although an explicit formulation of this rule was not found, it is clearly implied in a 2009 GAO report: "*Contracts containing more than one contract type will be coded as the contract type representing the preponderance of obligations*" (Government Accountability Office, 2009).

Table 8: The financial features of a development contract

Contract feature	Summary
Base price: fixed price (FAR 16.202)	The contractor agrees to complete the development for a fixed cost. The contractor's profit margin will be increased if the development costs less than the bid price, and decreased if the development costs more. The fixed price is limited to the development work specified in the contract, and changes to the scope of work usually incur additional cost.
or	
Base price: cost plus fixed fee (FAR 16.306)	The contractor agrees to take as profit an amount equal to a percentage fee of the estimated costs of performing the work. If the actual costs are more or less the contractor's profits do not increase or decrease. The contractor's rate of profit does however change, because the base costs change.
and any or all or none of the following	
Over-run and under-run cost sharing (FAR 16.405-1 usually)	Over-run and under-run cost sharing can be used to blur the boundaries in risk/reward between cost-plus and fixed contracts. Under sharing arrangements, government and contractor agree to share in the costs if they overrun or underrun the targets. Sharing arrangements make fixed price contracts less risky for the contractor and cost-plus contracts more risky. The rate of return under these contracts is adjusted to reflect the risk adjustment of sharing.
Targeted incentive awards (FAR 16.4)	Incentive awards offer additional payments to the contractor, in theory for delivering additional value to the customer. The awards are usually linked to time, cost or performance metrics, but may also be awarded for programmatic achievements like working well with other contractors.
Price indexing (FAR 16.203)	Price adjustment removes limited risks from the contractor, usually which are outside the contractor's control. It is only required by the contractor as protection on contracts where the contractor is not fully reimbursed for costs. The adjustment is specified in advance and usually linked to changes in published indexes like the price of aluminium, price of labor, or general inflation.
Redetermination of price basis (FAR 16.205)	Redetermination of the price of a contract is used for contracts with significant design uncertainty. The contract contains a fixed price for a fixed period, followed by a ceiling price for subsequent periods. The initial fixed period is intended to resolve some of the uncertainties which affect price, allowing a more realistic price to be calculated for the subsequent periods.

Fixed price contract

A fixed amount of base payment occurs when a contractor promises to develop a system for a fixed price at the outset. The summary in section 16.202 of the FAR is succinct:

> *"[there is no] adjustment on the basis of the contractor's cost experience in performing the contract. This contract type places upon the contractor maximum risk and full responsibility for all costs and resulting profit or loss. It provides maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden upon the contracting parties."*

These advantages come at a price. The contractor is likely to include contingency amounts in the contract to provide for the uncertainties in development. There is no guarantee that a fixed price contract will be cheaper for the government than a cost-plus contract, even though the contractor has maximum incentive under the fixed price contract to minimize costs. The danger of the contractor overbidding is particularly high if either the customer does not well understand the costs of the system it is requesting, impairing the customer's ability to negotiate the cost downward, or if there is limited competition, which removes the incentive on the contractor to submit a competitive bid.

However, it is not clear that government contracting practice acknowledges this distinction. The Defense Acquisition University's ACQuipedia states:

> *"The most advantageous contract type from the Government's perspective is firm-fixed price, as the contractor has full responsibility for the performance costs and resulting profit (or loss). The most advantageous contract type from the contractor's perspective is cost-plus-fixed-fee, in which the contractor has minimal responsibility for the performance costs and the negotiated fee (profit) is fixed."*

For this reason, when fixed price contracts are suggested in circumstances of low competition, a competent and dedicated system engineering team is required. A low competition environment arises by design in most of the System Acquisition Structures considered earlier in this section.

When there is no adjustment to the fixed price for incentives it is referred to as a firm fixed price contract.

Cost-plus-fixed-fee contract

A cost-plus-fixed-fee contract pays the contractor a fixed amount of profit. It achieves this by reimbursing the contractor for costs incurred in performing the work and also paying an additional fee. The fee is usually expressed as a percentage of the total estimated cost of the project. For example, a contractor undertaking a cost-plus-fixed-fee contract on a \$1 million contract with a fixed fee of \$60,000 would usually be described as having a "cost-plus contract with a 6% profit".

It is critical to note that the fee portion of the contract (\$60,000 in the example above) is fixed at the start and is not adjusted based on the costs in performing the contract. The amount of cost reimbursement is adjusted to reflect the actual costs in performing the contract. Paying the contractor a percentage of actual costs has been illegal since the Second World War. This type of contract is prohibited in section 16.102(c) of the FAR, due to the financial advantage to the contractor of cost overruns, and corresponding misalignment of incentives between the contractor and customer wishes. The prohibition extends to all subcontracts let by prime contractors except for firm fixed price prime contracts.

Under a cost-plus-fixed-fee contract the contractor is still incentivized to deliver the project at or below the target cost, because, if the cost of the project is assumed proportional to "contractor effort," the profit per effort decreases as costs increase, although the profit remains the same. In practice, however, this provides a weaker incentive than the fixed price contract, where cost overruns are completely absorbed by the contractor.

Cost reimbursement is a key feature of government contracting. Its use is very limited in commercial circumstances, but used in government when *"the cost of the work to be done cannot be estimated with sufficient accuracy to use any type of fixed-price contract"* (Government Accountability Office, 2009). In practice, this is not a narrow gateway: $136 billion of cost reimbursement contracts were used in FY2008, in proportions between 33% and 100% of contracts awarded by randomly selected agencies. (Government Accountability Office, 2009).

Cost-reimbursement contracts have limits on "allowable costs", the types of expenditure which may be recovered. Vacketta states *"cost principles preclude or severely limit the recovery of certain ordinary business expenses which a company might typically allocate to commercial operations"* (Vacketta, 1999). However Scherer's study, although old, found that *"in 1960 non-allowable costs comprised 1.0%... Interest charges made up the largest single share of this figure"* (Scherer, 1964).The discrepancy in emphasis between the two appears to be that the administrative burden of tracking, categorizing and reporting costs included in a cost-reimbursement contract is unusual for commercially oriented firms, however the dollar amount of non-allowable costs is relatively small.

The administrative burden reduces the number of firms willing to contract with the government on large cost reimbursement contracts. When the work exceeds $500,000: *"requirements necessitate the development of relatively complex, government contract-unique accounting."* (Vacketta, 1999). The requirements are pared down for contracts under $25 million, however corporations with cost-reimbursement contracts in excess of this amount must fully comply with the Cost Accounting Standards. In examining cost-plus contracts in the space sector, it will be assumed the value exceeds $25 million and the full accounting rules are required.

One further consideration weighs in favor of the cost-plus-fixed fee contract. The government does not want to appear to be delivering windfall profits to defense contractors. In the absence of competition or sound understanding by the government's contracting officers, it is possible that defense contractors could make profits at rates that would be branded scandalous in the media. While the total cost to government under the fixed price contract may in fact have been less than the cost to government of same contractor operating under a cost-plus contract with a 6% profit margin, such a rational analysis is unlikely to grab headlines. This chain of reasoning led Scherer to conclude:

> *"It so happens...that minimizing the risk of loss is often just what the contractor prefers while minimizing the risk of windfall profit is what the government desires, and so the CPFF [cost plus fixed fee] contract provides a mutually satisfactory relationship."* (p133)

Overrun and Underrun Cost Sharing

It is possible to blur the boundaries between the fixed price contract and the cost plus fixed fee contract. Under the fixed price contract, the contractor is wholly responsible for cost overruns, and receives all the benefit of cost underruns. Under the cost plus fixed fee contract the government is wholly responsible for cost overruns, and receives all the benefit of cost underruns. Overrun and underrun cost sharing allows the contractor and the government to take percentage shares in the "pain and gain" involved in the contract.

For example, a contract could be structured such that:

- any overrun or underrun up to 10% of the target price is completely absorbed by the contractor;
- any overrun or underrun up to 20% of the target price is jointly shared 50 / 50 between the contractor and the government;
- any overrun or underrun greater than 20% of the target price is completely absorbed by the government.

This contract regime may deliver preferable affordability results because often the part of the development which poses the greatest risk for the contractor is the low-probability, high-consequence tail of cost overruns greater than 20%. If the contractor bears this risk it must significantly increase its fees to maintain a risk-reward profile acceptable to shareholders. The total responsibility for costs close to the target provides a strong incentive to deliver close to the target costs.

A drawback with this type of contract is that the incentives close to the target price only function when there is a chance of the target being achieved. For example, if halfway through development it is clear that overruns of 200% are likely, with 150% as an absolute minimum, the incentive ceases to function because there is no longer a correlation between contractor actions and the incentive returns.

This problem is compounded when the government is unable to estimate the target costs with certainty. This led the GAO to recommend that these should only be used where *"the government has a sound basis to estimate contract costs, but where uncertainties exist that make a fixed-price contract impractical"* (General Accounting Office, 1987, p. 1). In an attempt to improve, among other things, this situation, the Truth in Negotiations Act was introduced which requires contractors to give honest assessments of their view of contract cost to the government.

"Value Engineering", a watered-down version of overrun and underrun cost sharing, is included in section 48 of the FAR. Value Engineering means the contractor can propose better ways of performing the contract which save the government money. The contractor shares in the savings. The contractor is permitted to receive between 25% and 50% of the savings on a fixed price contract, and between 15% and 25% on a cost-plus contract. Section 48.105 of the FAR contains a provision which prevents value engineering payments from being double counted under other incentives.

Value Engineering is less powerful than general overrun or underrun cost sharing because it operates only at the instigation of the contractor (or, in some cases, if the government directs the contractor to examine a particular piece of the acquisition for value engineering). The government also has discretion as to whether or not to accept a Value Engineering Change Proposal, introducing a risk for a contractor that it will invest effort in a value engineering proposal that the government rejects as not worthwhile.

In another way Value Engineering is more powerful than overrun and underrun cost sharing because it can apply to phases of the acquisition beyond those the contractor is responsible for, for example operations under a design and manufacture contract.

The GAO has been critical of value engineering: *"the VE program has made a minimal contribution to cost reduction in DOD"* (Government Accountability Office, 2003, p. 2). It attributed the failure of value engineering to starting value engineering too late, its limited use throughout the services, and the *"cumbersome processes required to implement the program"* (Government Accountability Office, 2003, p. 2). Although the GAO does not mention it, it is likely there are practical difficulties in implementing value engineering as well, since operations cost savings can only be estimated during the manufacture period.

Sensibly, the NASA FAR Supplement states that Value Engineering shall not be included in any R&D contracts which are simply restatements of the contractor's proposal, on the other hand it encourages them where NASA specifications are written. The principle is that contractors should not benefit from their own ill-thought proposal, but should be rewarded if they improve a poor NASA concept.

The concept behind value engineering, incentivizing contractors to find cost savings that benefit the government rather than themselves, is an important one for improving contractors' incentive to identify and implement commonality during the design phase. It appears the value engineering approach as it currently exists does not achieve this, however.

Incentive contracts

Overrun and underrun cost sharing is one method of delivering an incentive to contracts. However, contracts do not have to offer incentives based on cost considerations alone. Incentives can be allocated based on almost any other parameter, including schedule and technical performance. The contractor is paid the appropriate fixed price or fixed fee for simply meeting the requirements. The contractor is paid additional fees for delivering at a higher level than the requirements dictate. The idea of using incentives in aerospace contracts is almost as old as flying itself, with the contracts won by the Wright brothers for the Army's first heavier than air machine stipulating incentives for flights faster than 40 miles per hour (Sokolow & Green, 1999). Equally, incentives on NASA contracts are by no means new. A 1962 article documented the increasing reliance by NASA on incentive contracts (H. Taylor, 1962). Tom Kelly notes the same: *"In March 1965 Joe Shea kicked off a major exercise aimed at renegotiating Grumman into an incentive contract"* (Kelly, 2001, p. 146). Figure 31 is reproduced from Levine and shows a swift growth in incentive contracts through the Apollo program, as well as an increasing variety of incentive combinations.

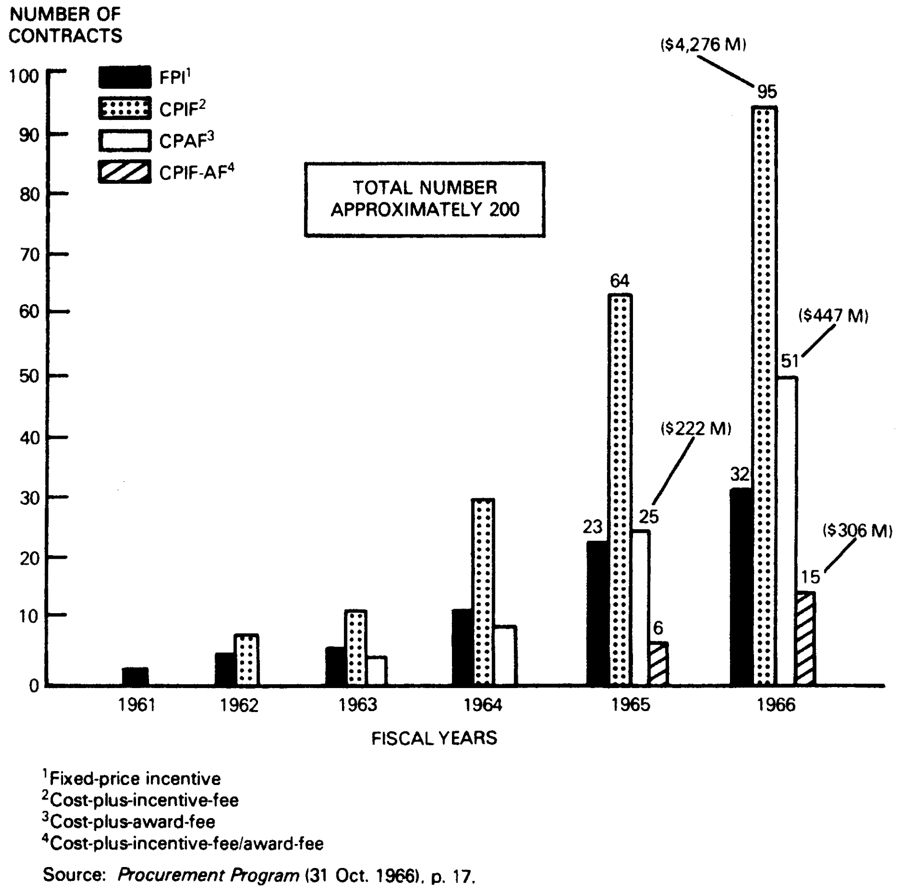

Figure 31: Growth in NASA incentive contracts (Levine p108)

Incentives can either be tied to fixed metrics, or considered subjectively by the customer at the conclusion of the contract performance. In the latter case the incentive is referred to in the FAR as an "award fee" and is *"an award amount, based upon a judgmental evaluation by the Government, sufficient to provide motivation for excellence in contract performance"* (FAR section 16.305). The FAR recognizes the government costs associated with subjective evaluations of contractors and requires that award fee incentives are not used unless the *"administrative costs…are not expected to exceed the expected benefits"* (FAR section 16.404(b)(1)). Award fees have been criticized for being too routinely awarded, for example awarded in cases where performance was simply satisfactory and not excellent (Government Accountability Office, 2007c). This requires fortitude, competence and independence on the part of the government evaluation committee. Details of the incentive structures of current programs are difficult to come by because of confidentiality. Belden however gives the following incentives from a 1960s era satellite development contract. Cost was an 80/20 share ratio, schedule was approximately a $5,000 penalty per week late for the first month, and $20,000 per week after that to a maximum of $66,000 and performance was based on the ratio of commands given to commands executed, with a zero-incentive for 80% performance sliding up to a bonus of $132,000 for 100% performance and down to a penalty of $132,000 for 60% performance (Belden, 1969).

Incentive contracts are frequently used by customers in complex engineering situations where trade-offs between cost, schedule or technical performance will need to be made during development. The inchoate system development does not permit the customer to fully specify the trades to be made at the outset, and meeting each time a trade is contemplated to re-write and perhaps adjust the price of the contract would be inefficient. Most of the development time would be taken up with meetings. Instead, *"the incentive structure should compel decisions as between cost, time and performance that are in consonance with the overall procurement objectives of the government. "* (US Department of Defense, Incentive Contracting Guide, p38, quoted in Scherer, p173).

Although incentive structures in contracts are powerful motivators to contract performance, they must be used carefully. The government should not rely on incentive targets being met, or even attempted to be met. Performance at the level specified in the requirements must be acceptable. The incentives must represent value for the government, in that the government must consider the improved performance to be worth the additional payment to the contractor. Poorly crafted incentives offer an opportunity for contractors to reap additional profit while making trades that are not necessarily in the best interest of the government: *"Because outstanding results may not be attainable for each of the incentive areas, all multiple- incentive contracts must include a cost incentive (or constraint) that operates to preclude rewarding a contractor for superior technical performance or delivery results when the cost of those results outweighs their value to the Government"* (FAR section 16.402-4).

A carefully written incentive contract where legal and technical teams work closely together can overcome the difficulties cited in the previous paragraph. A more fundamental difficulty with incentive contracts is whether they have a strong effect on the contractor teams which make contractor decisions. Scherer's study of a wide range of defense acquisitions in the early 1960s led him to conclude that incentive contracts were in reality not especially powerful for motivating contractors: *"Just as engineers become fascinated with the products they design to the point of seeking undue perfection, contracting personnel may well overestimate the effects of the instruments they design and administer. "*

However, the defense industry of the 1960s is separated in both time and purpose from the space industry of the 2010s and Scherer's conclusions may no longer be relevant. In drawing his conclusions on the inefficacy of multidimensional incentive contracts, Scherer uses two findings. First, market forces tended to encourage contractors to sacrifice profit margin or schedule for quality: *"Strongly motivated technical personnel at the operating levels are typically more concerned with perfecting the things on which they work than with profit maximization. "* Second, incentives did not translate to the people who did the work:

> *" our case study research in companies with profit sharing plans suggested that the plans failed to alter employee behavior. The common problem was that engineers and project managers were unable to perceive any correlation between their individual performance in such activities as tradeoff decisions and the size of the bonuses they received. .... "bonuses are nice to get, but you can't interpret them back as an incentive to make our plane fly higher, faster and so forth, at less cost." "*

Scherer notes that the effectiveness of incentives increases for small production runs and contracts with little follow-on work: "*development contracts with no follow on potential are clearly the exception in weapons acquisition although they may become more common in the field of space exploration"*. In these cases *"automatic multidimensional contract incentives may have more than a small marginal effect on contractor behavior"* (Scherer, 1964, p. 170). This is consistent with Kelly's recollection that, after NASA and Grumman Aircraft Corporation negotiated an incentive contract for the Apollo Lunar Module, "*Gavin and Mullaney held internal meetings to publicize the incentive provisions of the contract so that everyone working on LM would know what the specific short term goals and priorities were.*" (Kelly, 2001, p. 147)

The issue of the effectiveness of incentive contracts in the 2010s is investigated further in the scoping interviews and case studies.

On balance, incentives appear to be a powerful motivator of contractor behavior, but the effect of incentives on commonality is not straightforward. Incentives can be used to strike the right balance between cost and performance trades, which helps incentivize commonality. However, incentivizing commonality directly is very difficult. First, as commonality is not a goal in itself, maximizing the commonality to maximize the profit on the commonality incentive may not be the most desirable outcome for the government. Second, predicting the right commonality level in advance is impossible in all realistic cases because the amount of beneficial divergence or unanticipated reuse cannot be predicted in advance.

Incentivizing minimum lifecycle costs is an alternative, but also faces difficulties. First, calculating lifecycle costs depends heavily on data, and often the contractor is the best source of this data. Having the contractor calculate lifecycle costs on which its incentives will be based is unlikely to produce the best results. Rewarding a contractor at the end of development based on estimates of future lifecycle costs is troublesome because there will be considerable uncertainties around what the future lifecycle costs will be, making it unlikely the incentive will directly represent outcomes. Payment for yet-to-be-realized savings could be politically explosive if the savings fail to materialize and yet the contractor received a large incentive payment. The alternative, waiting until the lifecycle costs are incurred is also problematic, because few contractors will be willing to wait decades to receive incentive payments, the actual lifecycle costs will be influenced by factors outside the contractor's control like operating procedures, and finally the baseline operating costs in the absence of commonality will themselves be uncertain, making it impossible to calculate savings.

Price Indexing

Some contracts provide for contractor fees (or incentive targets) to be adjusted by reference to prices actually experienced by the contractor. These may be published indices or actual costs. For example, published indices reflect the cost of raw materials in particular sectors or the cost of labor. The changes in these indices from their values at the time of contract negotiation can be used to change fees or targets (FAR section 16.203-1).

The effect of these arrangements is to move the risk of input cost spikes from the contractor to the government. Such a clause may be beneficial for the government because the removal of external risks to the contractor like labor price increases should lower the contractor's bid price.

It is not likely that price indexing will have a significant effect on commonality, but it is included here for completeness.

Price Redetermination

Section 16.205 of the FAR provides for prospective price re-determination in connection with fixed price contracts. Essentially, a firm price is agreed for a fixed period and a ceiling price is agreed for subsequent periods. Renegotiation occurs after the initial fixed period for subsequent periods. The advantage of this approach is that much of the uncertainty is driven out of the design in the initial period and the associated risk need not be priced into subsequent periods. However, the contractor has little incentive to lower prices below the ceiling price unless there is competition at that stage of the contract.

Price redetermination may affect the price of commonality because commonality strategies increase the risk in the early phases of the contract. Acquisition strategies with renegotiation permit the government to renegotiate once the costs of commonality are better known. On the other hand, competition, which incentivizes realistic renegotiation tends to be suppressed under commonality strategies which may make renegotiation difficult.

Market forces

A discussion of contract incentives would be incomplete if it neglected the powerful forces acting on contractors which are not written into the contract. In practice, there are a range of market forces which incentivize contractors to think about more than just short term profit maximization when performing a contract. These have implications for designing an acquisition strategy because they affect contractor behavior but are harder to identify because they are not incentives printed on the contract. Four appear particularly prevalent:

- A bias towards quality to ensure future work is not compromised.
- A bias towards underbids on initial contracts with profits to be later recovered.
- A bias against subcontracting when the market offers few opportunities for new work.
- A bias towards lower profit rates on high-technology cost-plus contracts to improve corporate skills.

Most obvious is the incentive for corporate quality. Making poor products threatens the ability of the corporation to obtain subsequent products. This impacts the long-run survival of the corporation and therefore the corporation may act to improve the quality of the product even when this causes a reduction in short term profitability. One quote in Scherer's qualitative analysis summarizes this attitude: *"this isn't for any monetary considerations, but for our corporate reputation. There's nothing that will sour your customer like selling him something that doesn't work... if we're going to stay in business a thing's got to be good"* (Scherer, 1964, p. 162).

A second incentive is the idea that corporations will sacrifice short term profits on a contract in order to secure later profits. In the aerospace and military industries, corporations often look to production contracts, rather than development contracts, to make profit. In extreme cases, the development contract may be a loss-leader to obtain the development contract. *"Contractors have generally been willing to sacrifice initial development contract profits for the chance of earning substantial production follow-on contract profits once they are locked together with the government in a relationship analogous to a bilateral monopoly"* (Scherer, 1964, p. 156).

Corporations also have a long-run investment in staff. In a market with low opportunities for other types of work, contractors are incentivized to keep their staff busy on existing (cost-plus) contracts, rather than complete the work quickly and have idle staff. This extends to subcontracting. A firm is likely to minimize subcontracting in a low opportunity environment even when such subcontracting is an efficient strategy and the contractor could reap incentive profits from the lower development cost. The longer term forces acting on the corporation trump short term forces. It is not possible to definitively state how this will affect the project. It may improve the project if the subcontractors were equal or lower quality than the prime by keeping the design team better coordinated. In contrast, if the contractor normally subcontracts because the subcontractor has better expertise, then quality will suffer if the contractor keeps work in-house.

The investment in staff is closely tied to an investment in knowledge. High-risk, cutting edge projects offer the chance to obtain corporate skills that can be later applied to profit making projects. The canonical example is DuPont's assistance on the Manhattan Project for a cost-plus-$1 fee. DuPont was sensitive to allegations of profiteering leveled at it in the First World War, but also emerged from the Manhattan Project in a leading position to build the United States' civil nuclear power plants (DuPont, 2011). Government aerospace projects offer similar opportunities to companies willing to invest in learning while being paid by the government.

These ideas are important to commonality. Market forces lead corporations to minimize short term profits to make long term profits, the same constraint that operates when an initial investment is made to develop a platform. Corporations are willing to sacrifice short term profits to achieve a *"bilateral monopoly"*, and commonality across the exploration architecture increases the potential for monopoly situations to arise.

In concluding this analysis of extra-contractual incentives it is worth noting that Scherer lays a heavy emphasis on their effectiveness after his extensive case work: *"if firms tend to maximize any kind of profits at all, it is the long run variety"* (p321). Scherer's work was conducted in the Cold-War defense contracting environment and this sentiment seems to be in contrast with the popular view of modern space contracting, but is worth noting.

Summary: Effect of Contract Payment Provisions on Commonality

In summary, contract type has a strong effect on commonality:

- Fixed price contracts encourage minimum up-front expenditure by contractors, which usually hampers commonality identification, while cost-plus contracts may incentivize an over-emphasis on performance at the expense of value. Degrees between the fixed price and cost plus extremes can be achieved through overrun and underrun sharing.
- Incentives other than price can be used to better align government and contractor goals, however it is difficult to achieve an incentive which operates directly on commonality. Award fee structures may be better suited to assessing commonality, but rely on a competent customer system engineering team such that the contractor has confidence it will be fairly assessed.
- Price redetermination may be a strategy which could be used to encourage the exploration of commonality ideas early in the contract at low risk to the contractor.
- Contractors are also affected by longer term profit motives shaped by market forces outside the contract, which must be considered when designing incentives.

Contract Deliverables

Closely linked with how the contractor is paid is what the contractor must do. Thus far it has been implicitly assumed that the contractor performs design, development and perhaps some commissioning as well (Figure 32). That is not the only way to achieve an acquisition goal. Two other methods are considered below. One is to simply acquire a service rather than paying for development (Figure 33). The second is to pay for development but extend the contracting relationship to cover operation also (Figure 34). The latter two methods connect the development contractor financially to the operating stage of the project – often the phase which benefits most from commonality – and are therefore more likely to encourage commonality in the development phase.

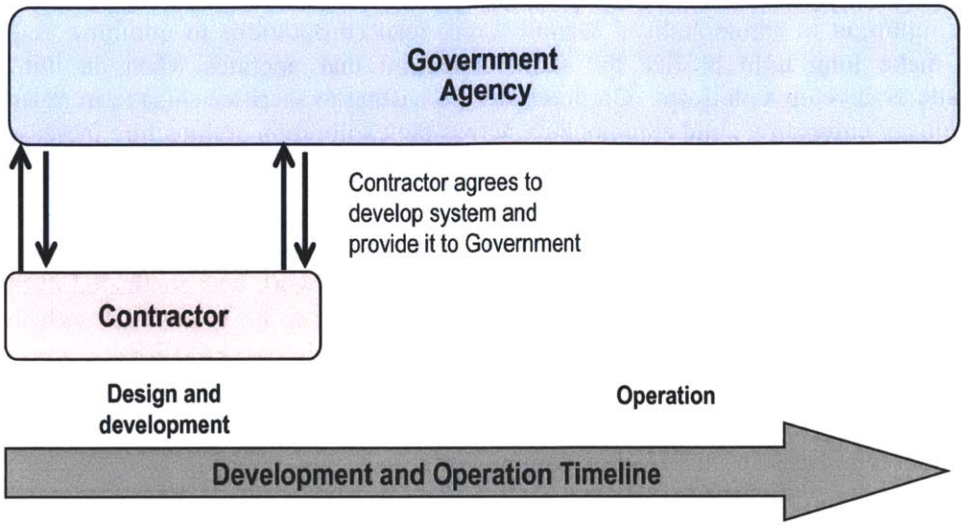

Figure 32: Conventional system acquisition

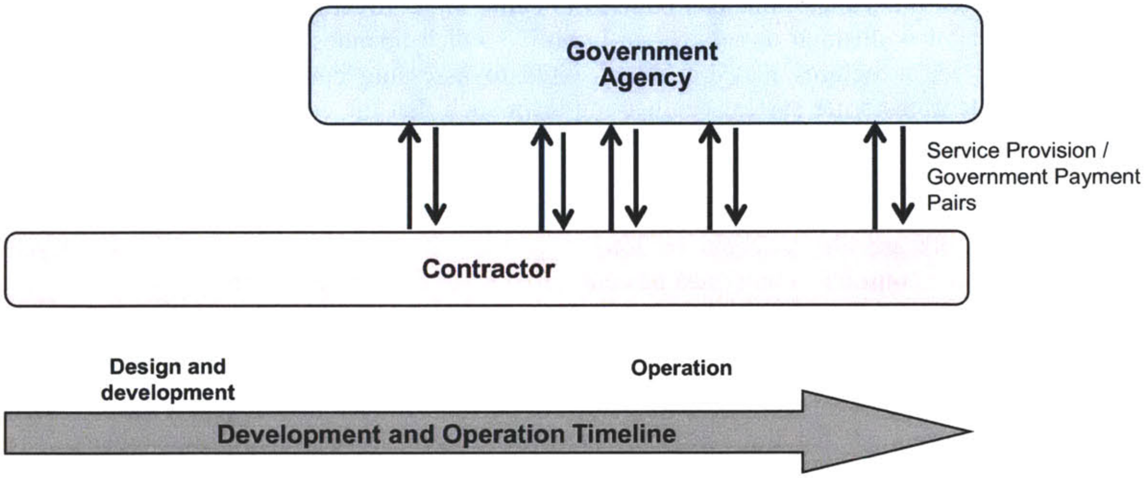

Figure 33: Acquisition of a system using a service contract

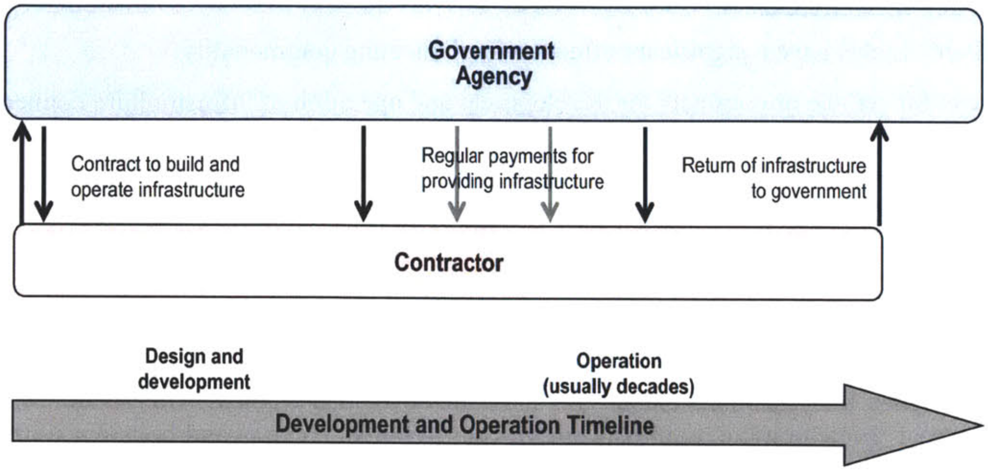

Figure 34: Acquisition of a system where the contractor operates the infrastructure

The service contract is unusual in space acquisition and deserves further explanation. In this type of contract, the customer does not pay for a physical item, but rather for a service to be provided. For example, the US government is not paying directly for the entire development of commercial crew launch vehicles, but will pay for services on a per-launch basis. Similarly, Hamilton Sundstrand is being paid per liter for water produced from its Sabatier reactor on board the International Space Station, rather than as a lump sum development fee.[8] Other government branches have used contracts for services because it allows funds for operations and maintenance rather than procurement to be used for the contract (Government Accountability Office, 2006). The effects of this contract type are that the service provider is not paid if the service is not provided, which incentivizes quality, and the service provider is responsible for the ongoing maintenance of the product in order to continue to provide the service. Of course, contracts for service only work well if there is price competition, otherwise any inefficiencies in design or operation are simply passed through to the customer as higher rates for the services.

The third type of contract shown above is one where the contract itself requires the contractor to operate the infrastructure in some form. This structure is most often seen where civil infrastructure is "project financed". The up-front funding for the project is raised from debt lenders (banks) and equity participants (shareholders), and the funding is paid off over time from profit in operating the project. Examples of output include oil from an oil rig, water from a desalination plant or coal from a mine. These "bankable" products do not yet exist for human spaceflight, making a project finance revenue stream only possible by a government guarantee, for example a payment of $1 billion for each successful landing on the moon. Such a guarantee would tie future Congresses and Administrations to the policy goals of this one, and would therefore be difficult to implement.

As a secondary consideration, the rates at which debt is lent to projects depends largely on the resale value of the assets which that debt purchases. Mining trucks and oil rigs have reasonable resale value; pieces of launch vehicles do not (particularly in the most likely default circumstance where the United States has abandoned its space program). Project financing is not suitable for the space sector.

Optimists may point out that SpaceX received significant funding from Draper Fisher Jurvetson (Needleman, 2009), however that funding is tied to the satellite launch market, which does have a bankable product and for which there would be buyers of, in particular, SpaceX's intellectual property in the event of an insolvency.

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[8] A more detailed discussion of contracts for service is summarized in the scoping interviews.

Summary: Contract Deliverables

The Contract Deliverables have a significant effect on implementing commonality.

- Contracts for service or contracts for development and operation of infrastructure connect the development contractor with the lifecycle costs of the product and are more likely to incentivize examination of commonality.
- Contracts for service are more appropriate for a human exploration architecture than project finance approaches.

Contract Phasing

The contract deliverables considered above extended the usual concept of a development contract into the future, allowing the system developer to operate the developed product. This section will examine the effect of shortening the usual concept of a development contract and breaking it into separate concept, design and manufacture phases, illustrated in Figure 35. Corporations which win early design contracts and perform well have an advantage going into future phases of the design.

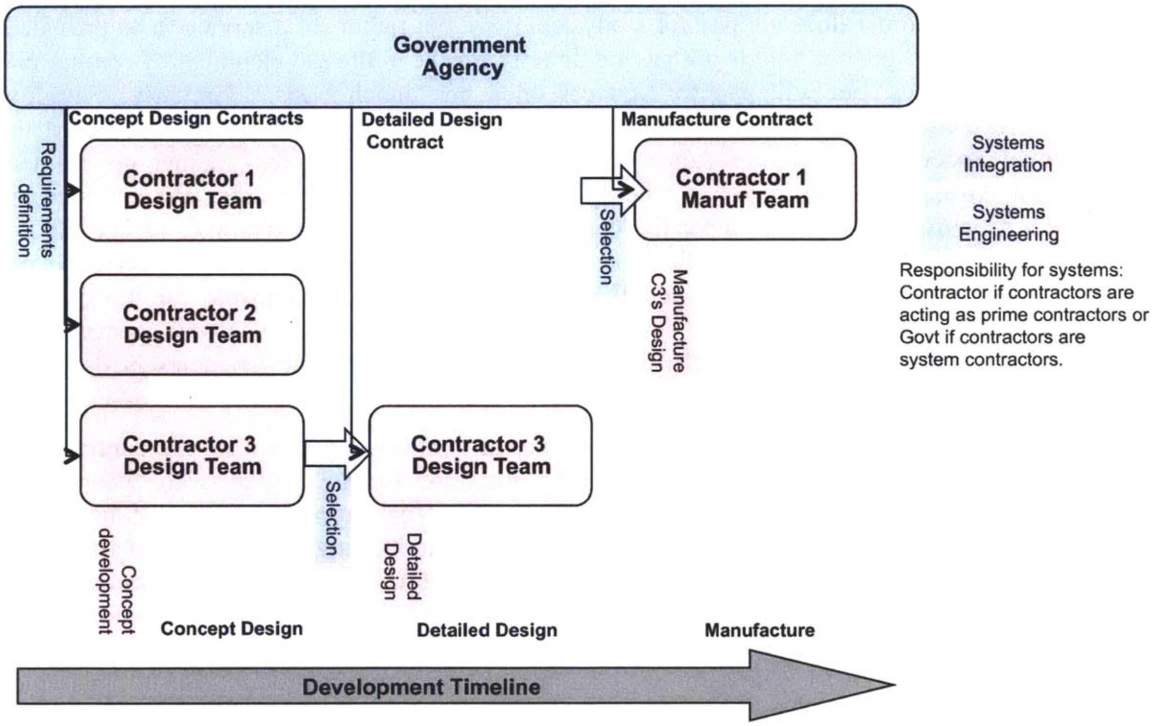

Figure 35: Contracts phased over time

There are several reasons why requiring companies to bid on shorter contracts is a good idea. Contracts for concept designs are cheaper than full development contracts. This means that several concept designs can be let and the best ideas captured. Bergstrom points out how this approach evolved between the Apollo and Shuttle programs. NASA teams made many of the critical design decisions for the Mercury, Gemini and Apollo spacecraft, but by the time of the shuttle "*the contractors were strengthening headquarters' ability to effect the design it wanted...the profusion of ideas, and the engineering studies of them, were giving NASA the data it needed to make the optimal trade-offs among configurations*" (Bromberg, 1999, p. 89).

This approach carried to its extreme results in "fly-off" acquisition, where contractors build a fully working version of their proposed design and compete with one or more other contractors for the final production order.

Two main reasons make the fly-off unsuitable for NASA acquisitions. First, the high proportion of total system cost which is spent on design means that the advantages of the fly-off come at a higher cost. Government must pay for the extra design effort either by contemporaneously subsidizing it or by offering sufficiently lucrative contract prices and volumes that the risk of not winning the fly-off is outweighed by the upside. Note that Figure 36 is based on DoD space activities, which do not have the ongoing operating expenses of human spaceflight. Satellite operation is largely a matter of following the manual and crossing one's fingers. Human spaceflight involves ongoing interaction between crew and ground, and an operating phases that includes repeated launches of hardware. This *may* make the fly-off more attractive for human spaceflight programs than for satellite programs.

Second, there are significant interrelations in the human space architecture as a system-of-systems. For example, during design of the lunar module in Project Apollo, there was a delicate interrelationship between the reduction of performance margins on the Saturn V and the weight envelope on the lunar module. In a fly-off, the product evaluation must be taken out of its context with other design elements and evaluated on its own parameters. This means that flexibility to move envelopes between systems during design is lost.

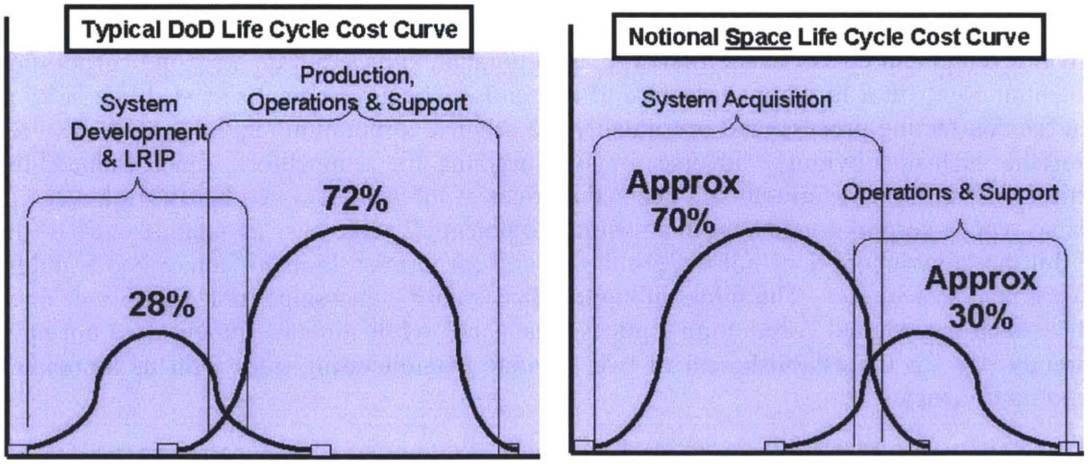

Figure 36: Contrast between terrestrial and space acquisition cost profiles (Brown, 2008)

Having discarded a full fly-off approach in the NASA context, the question arises of whether phasing of design or development contracts might be appropriate. Funding multiple design studies in the early stages of a project has become routine now as an increasing amount of space expertise resides outside NASA. A more controversial approach extends simultaneous competition to the manufacturing phase, with independent designs. A recent example of this approach is the dual-sourcing of engines for the joint strike fighter. The debate in Congress summarizes the pros and cons of this approach neatly. On the one hand, the fixed capital costs of design and manufacturing lines must be paid for twice by the government. On the other, continuous competition delivers lower prices to the government throughout the lifecycle of the aircraft.

The Federal Acquisition Regulations recognize the benefit of extending competition, but also accept that it is impossible to precisely legislate for the right duration of competition government wide. Subpart 34.002 requires that *"Agencies acquiring major systems shall... (b) sustain effective competition between alternate systems and sources for as long as is beneficial."* Occasionally, this can be a difficulty in the aerospace industry. In one instance in 1997, Boeing *"declined to bid on a six billion dollar contract, leaving Lockheed Martin the sole bidder"* (Bromberg, 1999, p. 177).

An application of contract phasing related directly to commonality includes an additional phase in the contract for the identification of commonality opportunities. During this pre-design phase, the contractor prepares a report on possible commonality options and the estimated return from taking those commonality options. This focuses attention directly on possible commonality opportunities and avoids the possibility that commonality is overlooked altogether. However, the contractor may not yet have the experience with the system necessary to make informed decisions at this point. If the commonality investigator is not the same contractor which develops the system there is a risk the system developer will ignore the commonality exercise.

Leader / follower contracts are a halfway point between the monopolistic position that manufacturers of complex systems find themselves in, and the inefficiencies associated with paying two corporations to design a complex system. In leader / follower contracts, one corporation is primarily responsible for development, while the other corporation offers an alternative at a lower switching cost than restarting the project, but at a higher cost than running two simultaneous development projects.

There are two broad types of leader / follower contracts which achieve competition without excessive development costs. In the first type, a corporation agrees to train a second corporation as a potential competitor in the manufacture of its goods. The government sets such a condition early in the contracting process, and presumably the original corporation requires an uplift in fee to undertake such an obviously adverse move as training the competitor. Once trained, the competitor sells to the government and keeps the prices of the manufactured hardware lower. In the second type, a corporation is kept in a position to potentially take over the manufacture of the goods, but the government does not require the second corporation to manufacture goods unless the government so requests. The threat of competition, rather than competition itself, is deemed enough to keep the original corporation's prices reasonable, while the government does not have to indirectly pay for the establishment of two separate manufacturing lines with its associated costs and inefficiencies.

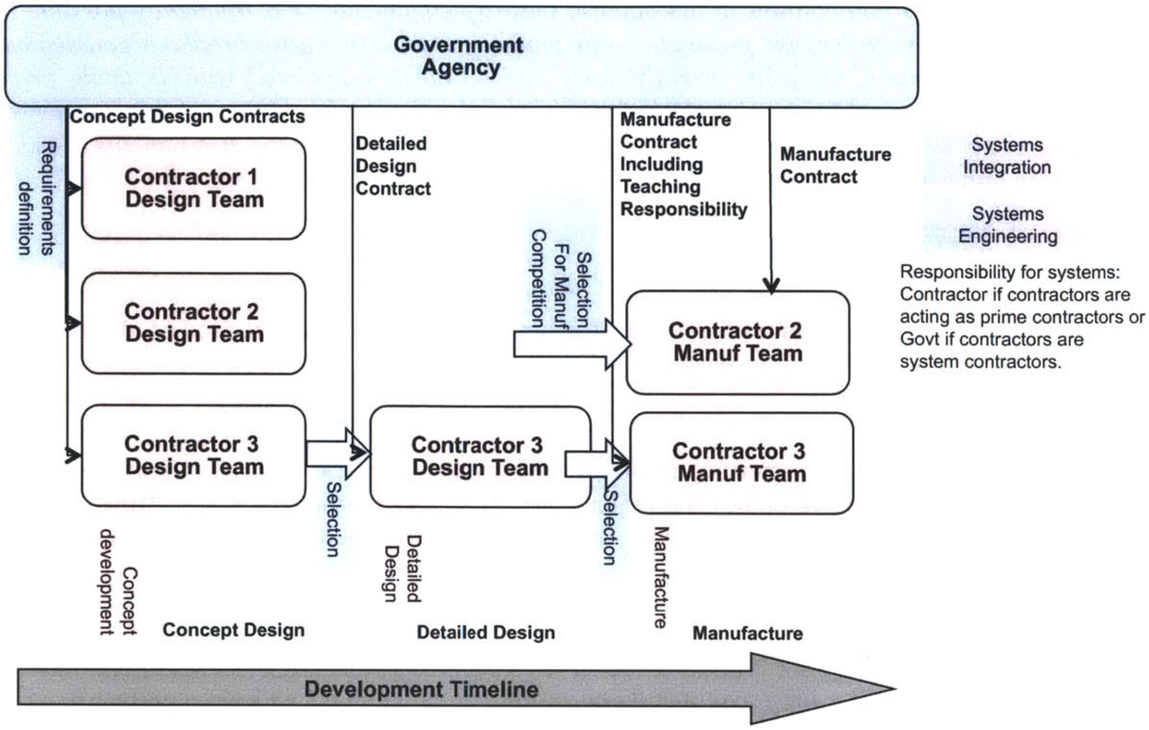

Figure 37: A leader / follower arrangement only implemented in manufacture

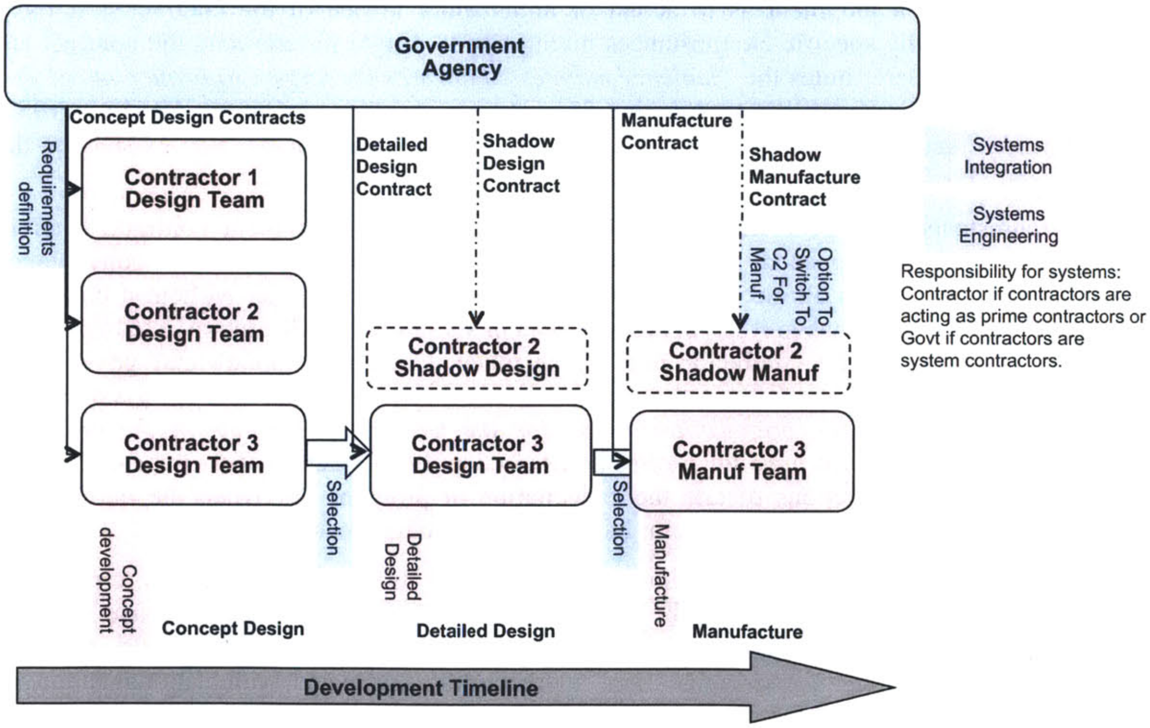

Figure 38: An unimplemented leader / follower arrangement

Scherer's analysis of competition in the defense industry concluded *"it is frequently possible to create competitive incentives for production efficiency through competitive breakout and second sourcing. Nevertheless, there are usually costs and problems associated with securing price competition on the production of technically advanced and complex items. A high order of judgment is required to determine in any particular case whether the prospective benefits of price competition outweigh the costs"* (Scherer, 1964, p. 128).

Summary: Contract Phasing

Contract phasing has some effect on commonality:

- Switching between contractors more frequently through the design process discourages rational investment in future commonality.
- Including a separate commonality identification phase can improve commonality outcomes.
- Shadow contracting can provide downward price pressure on a directed or long-term contractor, mitigating one of the major disadvantages of these structures. However, the shadow contractor comes at a cost, and there is a high switching cost associated with moving to the shadow contractor.

Contract Termination

Under some circumstances the government can terminate the contract with the contractor. The contractor has a powerful incentive to avoid those situations. Usual circumstances relate to cost, time or performance. For example, the contract may be terminated if the total cost expended crosses a certain ceiling, or if the contractor fails to pass a critical design review by a particular point in time. A contract may also be terminated without express contract provisions in circumstances where the contractor has not or is anticipated to not fulfill its contract obligations. Practically, making a judgment as to actual or anticipatory breach of the contract is a risky exercise which is why specific circumstances giving rise to a right to terminate the contract are often specified. Scherer notes the *"leniency manifested towards the large corporate contractor"* which the government showed in terminating 221 contracts worth a total of $8 million in 1957, and comments that termination for default on large contracts was virtually non-existent at the time (Scherer, 1964, p. 307).

These circumstances are generally less powerful incentives in government contracts than in commercial contracts, because all government contracts are also terminable "for the convenience of the government." This allows the government to terminate the contract without a breach of contract by the contractor when it is *"in the government's interest"* (FAR section 2.101). At this point, the payments to the contractor become as much a matter of policy and government reputation as law. The FAR requires that termination *"should compensate the contractor fairly for the work done and the preparations made for the terminated portions of the contract, including a reasonable allowance for profit"* (FAR section 49-2). Termination for convenience is used when policy directions dictate the cancellation of programs, or when the outlook for programs looks bleak despite the contractor having committed no breach so far.

The government must generally be cautious about exercising its rights to convenient termination too liberally. While such rights may be helpful in a current tight situation, overuse leads to contractor distrust of the government and eventually to a reluctance to bid on contracts. It is effectively an expression of "sovereign risk" more closely associated with nationalization of utilities or resources in the third world, and, like sovereign risk is likely to drive up prices in the industry generally.

Summary: Contract Termination

Contract termination in itself does not appear to have a direct effect on commonality. However, the historical reluctance by the Department of Defense or NASA to terminate projects until compelled to do so by Congress does have an effect. Properly implemented commonality encourages affordable projects and requires constant consideration of benefit-cost trades. A reluctance to terminate contracts which do not meet these criteria decreases the incentive for companies to implement commonality.

Insight and Oversight

A further category of contract provisions do not instruct the contractor on what to build, but rather mandate part of the organizational structure that oversees the development. In this respect these provisions are more concerned with the process of development than with what is actually developed. NASA contractors are often required to allow a NASA team to inspect progress on the development, often on a daily basis. NASA representatives work full time at the contractor facilities. This has five advantages:

1. NASA representatives supervise methods and processes to ensure they are being carried out correctly
2. Formal approvals and inspections which are required before work can proceed can take place more quickly with permanent NASA representation at the facility
3. NASA representatives are part of a continuous reporting chain back to senior NASA managers, which incentivizes ongoing efficient performance by the contractor and identifies potential programmatic problems early
4. NASA representatives serve as a conduit into NASA's extensive human spaceflight knowledge base and can share that knowledge with the contractor to improve the product
5. Continuous oversight allows cost structures like "cost plus" contracts to be used with greater confidence in the contractors' estimates of costs.

A more formal expression of the oversight function used across government is the Earned Value Management System (EVMS). The FAR requires that the EVMS is used for all major projects. EVMS establishes a baseline of work packages to be undertaken and then assesses contractor performance against the time taken for completed work packages and the cost taken for completed work packages (Rendon & Snider, 2008, p. 231). EVMS focuses only on the *development* aspects of a system, rather than the performance of the system during operations. In effect, EVMS is a system of metrics intended to be as precise as possible in measuring the development performance of a contractor against the target development performance.

Aiming for such development certainty does not complement commonality attempts. If commonality is already planned in the requirements given to the contractor, the EVMS is unlikely to account for divergence. Accordingly commonality will appear to the contractor as a difficult process to implement, as divergence drives actual cost and schedule away from predicted cost and schedule. Another drawback is that EVMS focuses solely on development. In the event that the contractor is required to identify commonality opportunities, such a focus is unlikely to incentivize the contractor to consider full lifecycle costs in their design and development, reducing the likelihood that commonality that delivers operating phase benefits will be identified. Finally, the EVMS puts cost and schedule pressure on the contractor which makes it unrealistic for the contractor to consider undertaking additional work to improve commonality with variants built by other contractors.

Summary: Insight / Oversight

The supervision culture that is already a part of NASA has implications for commonality. Contractors remain in close contact with NASA, making communication of small commonality changes easier and faster. If the NASA overseers have a good understanding of the project outside the particular piece they are asked to supervise then they can also contribute by helping to generate the visibility to identify new commonality opportunities, and also by identifying the causes of divergence early so that the divergence can be managed.

Using the EVMS does not normally account for the "overhead" of commonality implementation both from the perspective of the initial investment in commonality and the subsequent cost of managing divergence. This would be likely to discourage commonality attempts.

Intellectual Property

The intellectual property terms of a contract are an important facet of cross-contractor commonality. The essence of cross-contractor commonality is reuse of other contractors' designs. Such reuse is illegal without first securing intellectual property rights to the design. The provisions of the contract dictate the rights that customer, prime contractor, and system contractor have in intellectual property developed during the course of the program.

Intellectual property includes patents, trademarks, copyright, rights in data and moral rights, and engineering designs are likely to fall under either "patents", "rights in data" or "copyright".

The most straightforward case is the transfer of intellectual property rights from the company which developed the design ("originator") to the company which is receiving the rights ("recipient"). At one end of the spectrum of transfers which might take place is the complete transfer of intellectual property from the originator to the recipient. If this occurs, the recipient has full rights over the design, almost[9] as if they had designed it themselves. More moderately, the originator may give the recipient a license to undertake activities with the intellectual property but without ceding full rights. For example, the recipient could be given the rights to manufacture a particular design for five years only. Licenses can be exclusive, where the right to manufacture may not be given to anyone else. In practice, the terms of a license can be modified to suit the particular commercial needs of both parties. The parties will decide between themselves the value of the intellectual property.

When two companies work together to develop a product, for example as customer and supplier, the terms of the development agreement will determine whether intellectual property developed by the supplier belongs to the customer or supplier. If the development agreement is silent on intellectual property, then arguments are likely if any valuable intellectual property is developed.

The transfer of intellectual property from a government contractor to the government is more complicated. Part 27 of the FAR governs the intellectual property provisions of acquisition contracts. Examining the FAR, the NASA FAR supplement section 1827, and the National Aeronautics and Space Act 1958 indicates that the Government has very strong *theoretical* rights in intellectual property developed by its contractors. However, two factors mitigate government rights in practice. First, the government appears to have, on a policy basis, decided not to press its intellectual property rights as strongly as it could. Second, the provisions depend on a clear delineation between intellectual property developed with government funding and that developed with private funding, which breaks down in complex projects which combine both private and public funding intertwined over time.

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[9] In some cases, especially where the design approaches a work of art, the originator may retain "moral rights" in the design, essentially the right to be identified as the creator perhaps with some control over modification. This situation is unlikely in the engineering context of this thesis.

There is no doubt that the government has strong theoretical rights in inventions generated under government contracts. Section 20135(b) of the National Aeronautics and Space Act states that if an invention is generated by any person involved with a NASA-issued contract, whether they are at NASA or a contractor or elsewhere, then that invention becomes "the exclusive property" of the United States. To enforce this, no aerospace related patent may be issued anywhere in the United States unless the applicant for the patent proves that the invention was not made under a NASA contract (Section 20135 (d)). If the invention is made under a NASA contract, the Administrator may waive NASA's rights to the invention, however the United States at all times retains *"an irrevocable, nonexclusive, nontransferable, royalty-free license for the practice of such invention"* (Section 20135(g)). A similar right is given under the FAR where *"any invention of the contractor made in the performance of work under a Government contract"* automatically gives the United States a non-exclusive license in the invention (section 27.302(c)) and "march-in" rights to force grant of a license to third parties (section 27.302(f)). The same rights of the United States apply to the intellectual property of any subcontractor to the contractor at any tier (27.304-3(a)). There are some exceptions for small businesses.

The government also has strong rights in technical data and copyrights under sub-part 27.4 of the FAR. The Government receives "unlimited rights" in data which does not include trade secrets *"first produced in the performance of a contract"* (27.404-1). The government also has a right to data ("limited rights data") which contains trade secrets or confidential information, but must not disclose the data outside the government or use the data for manufacture (27.404-2(c)(1)).

The armed services have an additional category of data rights which operate halfway between limited rights data and unlimited rights data. "Government purpose rights" apply to data which is developed partially from private funds and partially from government funds. Government purpose rights allow the government to disclose *"for competitive procurement but not for private manufacturing"* (Duberstein, 1988, p. 26).

Despite these broad rights, intellectual property in contracts was cited as a key obstacle in the scoping interviews and case studies such as Rhodes' examination of the Constellation Space Suit System and the JTRS. Unfortunately, no specialist government intellectual property lawyers responded to requests for interviews for this thesis, and consequently the analysis below may not capture all the practical obstacles to giving the United States rights in intellectual property.

Despite the author's lack of a guide in navigating the complex intellectual property provisions in the FAR, two principles are clear. First, there are clear policy statements that reflect a government duty to strike a balance between contractor and government rights. *"Agencies shall balance the Government's needs and the contractor's legitimate proprietary interests"* (27.402(b)). The NASA FAR supplement states *"it is the policy of NASA to waive the rights (to acquire title) of the United States (with the reservation of a Government license...and march-in rights...if the Administrator determines that the interests of the United States will be served)"* (1827.302(b)(ii)). The supplement also states that "*the contractor is normally granted... a revocable, non-exclusive, royalty-free license in each patent application"* (1827.302(i)), which goes beyond the strict FAR requirements. Finally, the supplement acknowledges that its technical data rights in commercial items should be *"kept to the absolute minimum consistent with the purpose for which they are being procured"* (1827.406). The FAR itself states that *"the government recognizes rights in data developed at private expense and limits its demands for delivery of that data... [to] only those rights essential to its needs"* (27.102). The patent rights are designed to *"encourage maximum participation of industry in federally supported research and development efforts"* (27.302), which necessitates restrictions on the government's rights to appropriate industry's research.

Second, the provisions of the FAR contain significant grey areas when applied to complex development projects which intermingle hardware and software. The provisions depend on a clear delineation between intellectual property developed with government funding, and that which depends in some way on achievements made with private funding. For completely new research contracts such a division may be possible, but in the development of hardware projects the contributions of government and contractor are likely to have intertwined to an intractable Gordian knot. Some components are likely to be developed privately, perhaps at the subcontractor level, and others may have been developed under previous government projects. There is also a question over how much change separates a minor modification from a project that is so extensively modified that it is deemed to be a new development. Finally, the division between a patentable invention and the generation of technical data is difficult to make in the case of hardware-firmware-software interactions.

An attempt to strike a halfway point between the needs of the government and the needs of the contractor is the concept of "form, fit and function data", defined in section 27.401 of the Federal Acquisition Regulations. Governments (or their system integrator delegates) require this data to successfully integrate complex systems, and contractors are more willing to make mere interface data available than the entirety of the design.

The importance of intellectual property to commonality is high. Without the intellectual property rights to projects which have been developed it is exceedingly difficult for the government to allow multiple corporations to build the same common system. Without intellectual property the government is beholden to a single supplier, leading to a choice between the price rises often associated with a monopoly or new developments which abandon commonality. Proper management of intellectual property will be a critical determinant in the success of any acquisition program.

Summary: Intellectual Property

Intellectual property has a very strong effect on commonality:

- NASA has very strong intellectual property rights in the designs of its contractors which it could use as part of a more extensive commonality strategy. It chooses not to for policy reasons.
- Successful intellectual property for re-use in space systems will need to consider hardware, software and any intermediates.
- Rights to intellectual property should be agreed at the outset, before it is clear which organizations will benefit from particular provisions.

Socio-Economic Programs

It is worth noting that government acquisition requires that a wide range of socio-economic programs are considered, from the Buy American Act to the Small Business Act to the Javits-Wagner O'Day Act (support for people with disabilities). Most of these acts are concerned with furthering social goals through government acquisition. As many commentators have noted, such a multiplicity of goals from government acquisition necessarily means a dilution of efficiency when measured against any one goal (such as development cost). Two socio-economic programs have more direct impacts on the acquisition of architectures with commonality.

First, the Small Business Act encourages the use of small businesses in government acquisitions. Using small businesses means that more corporations will be involved in the supply chain at any one time, and also that more corporations will be involved over time because the duration of existence of small businesses is generally lower than the duration of existence of larger companies. Further, small businesses are likely to simply go out of business at the end of their lifecycle, whereas larger companies are often absorbed into others, often maintaining their experience within the aerospace sector albeit under a different name.

Second, the Buy American Act which limits the purchase of foreign goods in government acquisitions. Section 25 of the FAR simply requires that *"A foreign end product may [only] be purchased if the contracting officer determines that the price of the lowest domestic offer is unreasonable or if another exception applies."* In practice, the impact of the Buy American Act on space hardware is supplemented by the need for wide Congressional support and by the close nexus between space hardware and national security manifested in the International Trafficking In Arms Regulations (ITAR), both of which make it politically infeasible to send aerospace work (and jobs) outside the United States. On the one hand, the limitation of the pool of contractors to those with significant presence in the United States tends to decrease barriers to commonality by increasing the likelihood that the same contractors will be involved in projects with commonality potential. On the other hand, if the space exploration infrastructure is multi-national then the Buy American Act and its policy undercurrents will hamper commonality. On a macro scale, European contractors may have to duplicate the work of US Contractors, and on a micro scale the acquisition of common components or subsystems in a GFE-type arrangement will be more difficult.

An analysis of the balance which should be achieved between commonality and these socio-economic objectives is left to others. It suffices to note here that it is not at all clear the balance should be struck in favor of commonality. For example, the inclusion of more small businesses in acquisition may increase the availability of innovative solutions with far more positive effects on acquisition than those associated with an increase in commonality.

Summary: Socio-Economic Programs

Socio-economic programs have some effect on commonality:

- An emphasis on small business in acquisition increases the variety of organizations involved in acquisition and in theory makes commonality more difficult to implement.
- An emphasis on United States products in acquisition decreases opportunities for international commonality in space exploration architectures.

Conclusion

This section has examined the possible contract structuring and contract terms which could be blended to create an acquisition strategy. Combined with sections 2.1, which addressed the nature of NASA's acquisition task, and section 2.2, which addressed commonality best practice, the necessary background to the investigation of NASA commonality acquisition has been set out. The following chapters will summarize the results of discussions with practitioners which are used to more fully grasp the advantages and disadvantages of different commonality acquisition strategies.

CHAPTER 3: RESULTS OF SCOPING INTERVIEWS

The previous chapter relied heavily on formal, published works in assessing NASA's acquisition constraints, best practice from commonality, and the range of available acquisition strategies. In using such sources, there is a danger that practical constraints on acquisition will not be unearthed, or the most recent developments will not be captured. To address this limitation, a series of semi-structured interviews were undertaken with a range of NASA, DOD, industry and academic personnel. The aim of the interviews was primarily to identify any methods in use to improve commonality in complex aerospace architectures, particularly between multiple contractors. In doing so, interviewees normally gave examples of successful commonality projects from their past experience.

Interviews were conducted between October 2009 and March 2011 with people in the positions listed in Appendix A. During this time period, presentations on commonality were made to the CAEG team (involving consultants, civil servants and contractors working on costing at NASA Langley Research Center), JPL's office of the Chief Engineer, the NASA Human Exploration Architecture Team, the NASA Cost Estimation Group, and a group of interested analysts at RAND Corp. The discussion after these presentations contributed to this scoping exercise.

The results of the semi-structured interviews answer six major questions:

1. Have any acquisition strategies been used by NASA or DOD which focus on commonality?
2. Which acquisition strategies – actual or potential – could affect the amount of realized commonality?
3. To what extent do US Federal Government acquisition regulation and practices limit the acquisition strategies available for commonality?
4. What types of NASA projects would most benefit from an acquisition strategy focused on commonality?
5. What factors drive commonality success?
6. What are the obstacles to successful implementation of inter-contractor commonality?

The short interviews were supplemented by analysis of available academic literature and government publications. Table 9 summarizes the answers to these questions, as they were at the end of the scoping phase of the thesis. The answers go some way to analyzing the acquisition of commonality, and are then further developed in the detailed case study phases of this thesis in Chapter 4.

Table 9: Summary of scoping interviews

Question	Answer
Have any acquisition strategies been used by NASA or DOD which focus on commonality?	Both NASA and DOD plan for commonality when writing project requirements during the architecting phase. Neither organization has widely used acquisition strategies to encourage commonality in later design phases.
Which acquisition strategies – actual or potential – could affect the amount of realized commonality?	The scoping discussions revealed a range of acquisition approaches which drive commonality. None of these are at the level of a comprehensive acquisition strategy, however many of them represent the state of the practice in NASA and DOD and are worth noting.
To what extent do US Federal Government acquisition regulation and practices limit the acquisition strategies available for commonality?	NASA acquisitions are governed by both the formal requirements of the Federal Acquisition Regulations (FAR) and general acquisition practice. The FAR is theoretically open to the adoption of innovative acquisition strategies, but the practical realities of fixed yearly budgets and an inability to commit to purchases in future years or across centers eliminate some commercially used commonality strategies.
What types of NASA projects would most benefit from an acquisition strategy focused on commonality?	High value projects in the early stages of development and facilities and ground support equipment are likely the best targets for commonality focused acquisitions, but there were a wide variety of opinions.
What factors drive commonality success?	Strong management leading to commonality success was a constant theme through interviews with project participants. Interviewees also pointed to the need for mandated commonality, clear examples of commonality benefit and firm requirements.
What are the obstacles to successful implementation of inter-contractor commonality?	All interviewees expressed concerns about the difficulty of implementing extensive inter-contractor commonality. An overriding theme was the lack of positive incentive for companies to work together, coupled with significant downsides for companies which cooperated like loss of intellectual property or market leadership.

Question One: Have any acquisition strategies been used by NASA or DOD which focus on commonality?

Both NASA and DOD plan for commonality when writing project requirements during the architecting phase. Neither organization has widely used acquisition strategies to encourage commonality in later design phases. The planned common projects or systems in the architecture are usually awarded to a single contractor.

NASA plans for commonality during program architecting, making tradeoffs between the perceived costs and benefits of commonality. A good example pointed out by several interviewees is the architectural commonality in the Ares launch vehicles proposed for the Constellation Program. Features of the Ares I / Ares V commonality were examined Figure 13. The interviewees pointed out in particular:

- NASA re-used aspects of the Space Shuttle Solid Rocket Motors (SRM) between the Shuttle and Ares launch vehicles.
- NASA designed the SRMs to be shared between Ares I and Ares V with minimal changes.
- NASA designed the J-2X engine to be used in the upper stage of both the Ares I and Ares V launch vehicles.
- NASA reused aspects of the Apollo-era J-2 design and technology in the J-2X.

This commonality was established with a small level of contractor involvement. Contractors were awarded design studies and contractor staff with special expertise are often seconded to some NASA teams. However, the design process which resulted in the Constellation Program was essentially an in-house development exercise by system architects within the Exploration Systems Mission Directorate within NASA HQ.

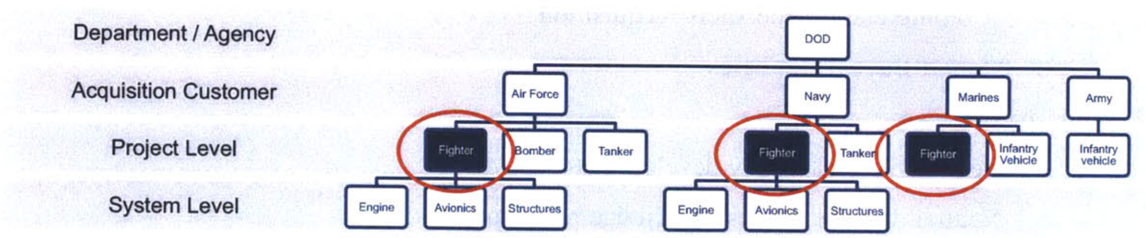
Once the architecture is decided, requirements are written for each of the elements which reflect that architectural vision. For example, the J-2X requirements are written in such a way that they represent the upper bound of both the Ares I and Ares V upper stage requirements. The contractor then designs and manufactures to those requirements, and the final product reflects the planned commonality. Several interviewees viewed this method of high-level architectural commonality development as the way to drive commonality into exploration architectures.

The DOD follows a similar pathway of early commonality intention. The DOD is exposed to more obvious architectural opportunities for commonality than NASA because it is responsible for distinct services, the needs of which often overlap. During the early phases of many defense projects, system architects examine opportunities for developing projects jointly with other services (McChrystal, 2009). Examples of jointly developed projects include aircraft, ranging from the TFX project to develop an aircraft for the Navy and Air Force in the 1960s to the recently developed Joint Strike Fighter used by the Navy, Air Force and Marines. The joint development of inter-operable radios in the Joint Tactical Radio System (JTRS) project is a non-aerospace example of commonality more fully examined in Chapter 4.

Interviewees often pointed to these joint DOD programs as good examples of commonality in systems-of-systems. The aggregation of demand from multiple services improves unit cost by spreading fixed costs over more units. Joint development breaks down when the cost savings of pooled development are outweighed by the performance compromises inherent in a joint project.

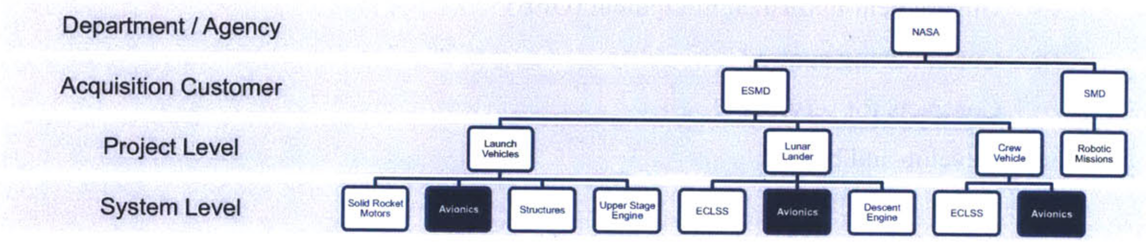
Joint projects are most often executed by a single prime contractor as system integrator. Most interviewees considered this approach to be the most sensible one to realizing commonality. For example, Lockheed Martin was the prime contractor for the Joint Strike Fighter. Lockheed Martin was then responsible for cost and schedule performance of the final product. Although there were requirements to develop a common aircraft, no specific financial incentives for commonality were included in the contract for the Joint Strike Fighter. Boas observed that this impacted the commonality actually realized: the *"contract incentive structure and budget constraints focus Lockheed Martin's development decisions on the minimization of development and Unit Recurring Flyaway costs"* (Boas, 2008).

Figure 39 and Figure 40 contrast the conceptual difference between the DOD approach, to drive commonality from the project requirements level, and the NASA approach, to drive commonality from the system function level. As the diagram shows, this is an obvious outcome when DOD's internal divisions have similar needs at the project level, and NASA's internal divisions have similar needs at the system level. Possible areas within NASA where the DOD structure would work are communications architectures like the Deep Space Network or Mars Orbiting Satellites which could be used by both human and robotic exploration.



DOD Approach: Allocate similar projects based on close requirements between acquisition customers to a single contractor to drive commonality

Figure 39: DOD commonality approach



NASA Approach: Allocate similar systems to a single contractor at the system level where aspects of function and form are defined

Figure 40: NASA commonality approach

Question Two: Which acquisition strategies – actual or potential – could affect the amount of realized commonality?

The scoping discussions revealed a range of acquisition approaches which drive commonality. None of these are at the level of a comprehensive acquisition strategy, however many of them represent the state of the practice in NASA and DOD and are worth noting.

The approaches raised during the discussions have been divided into three major categories. "Acquisition culture changes" describe ways that government organizations could change their approaches to acquisitions in general. "Industry-wide strategies" describe structural changes in the aerospace industry that could improve commonality. "Contracting strategies" describe approaches that could be used on particular acquisitions to improve commonality outcomes.

1. Acquisition culture changes
    - Formalized re-use
    - "Commercial off-the-shelf" acquisition
    - "Smart Buyer" strategies
2. Industry-wide strategies
    - Centralized technology development
    - Neutral organization as knowledge repository
3. Contracting strategies
    - Single corporation as system integrator
    - Joint ventures
    - Directed subcontracts
    - Government Furnished Equipment (GFE)
    - Commonality contract incentives
    - Contracts for services
    - Develop and buy-in

Acquisition Culture Changes

Formalized reuse

Reuse is the most basic form of Boas' three models of commonality development (Boas, 2008). However, it is straightforward to implement and several NASA centers have had success with formal re-use programs paid for as an overhead resource available to the center.

One example is JPL's Flight Hardware Logistics Program (FHLP). It creates a JPL-wide inventory of hardware which was ordered for a project but was not used during development. For example, flight spares or test articles are often ordered in anticipation of possible failures, and are unused if those failures do not eventuate. Under the FHLP, subsequent projects can reuse those pieces of hardware, which saves up to 1.5% to 2.0% percent on the total mission cost.

The initial driver for the FHLP was to address schedule inefficiency caused by the long lead time in certain space-qualified computer processors. The secondary driver was the cost reduction due to commonality. The program has a number of features to reduce the up-front barriers to reuse for program managers, such as web-searchable on-line inventories and shopping lists.

One drawback of programs like FHLP is that they do not incentivize the choice of easily reused hardware, for example by giving the original program some "sale proceeds" from the reuse. Such a market mechanism is unworkable under the accounting methods currently used at JPL. Inter-project transfers of completed systems either occur at the full cost of the system if the system is unused, or at zero cost if the system is used. There is no middle ground for a second project to help subsidize the development expenses of the first system.

Formalized re-use appeared most capable at the expensive component level rather than the system level. For example, the FHLP has had most success with items like flight computer chips, sun sensors and deep-space transponders, rather than more high-level systems. Clark & van Amrindge (2002) note common system development as a future goal of the FHLP. Analysis by the Constellation commonality team focusing mainly on cost savings showed that the benefits that can be expected from component level commonality are small compared to the benefits of commonality at the architecture or system level. The Constellation analysis is examined in more detail in the answer to Question 4 below.

COTS Acquisition

A strategy suggested by several interviewees as a way to increase commonality is to acquire "commercial off-the-shelf" parts ("COTS"). By buying commercial parts without alteration, the likelihood of commonality across projects or systems is increased.

This approach gives the government benefits of manufacturing economies of scale without the government having to consolidate bulk buys. It also gives some of the reliability benefits of and often access to large sample sizes for reliability analysis. Further, COTS parts can be very simply acquired under the FAR.

The most obvious disadvantage of COTS acquisition is that a commercial provider may not make a product that meets all of the requirements. This is a particular concern for space projects which often have unusual requirements, for example radiation hard circuitry, performance in a zero gravity environment or demonstrated ultra-high reliability. Additionally, there are often multiple commercial providers whose products are not common, and there is no guarantee in these circumstances that COTS acquisition will yield the operations phase benefits of commonality that come from standardized parts and processes. COTS acquisition may in fact decrease the commonality when compared to a NASA acquisition of a bespoke part from a dedicated production line.

Like formalized reuse, COTS acquisition focuses mainly on components and small assemblies, rather than architectural or system level commonality where the bulk of the commonality benefit is likely to occur.

Smart Buyer Strategies

The "smart buyer" approach involves government system engineers heavily in scoping and tradeoff exercises early in system development. This has three major effects:

- Government understands the costs of requirements better, and so can write a contract which includes only the requirements perceived as value for money.
- Government understands the level of technical risk, and so can choose a contract reward structure which apportions risk and reward between contractor and government appropriately.

- Government can participate more intelligently in the system tradeoffs that occur during development as cost, schedule and performance become more clearly defined.

One example given by an interviewee to illustrate the value of a smart buyer was the difference between commercial and military aircraft acquisition. The acquisition could proceed based on delivering a fixed level of performance for an negotiated price, as with most military contracts, or delivering negotiated performance for a fixed price, as with some commercial aircraft. A smart buyer will be able to pick the best of these strategies based on the best solution for its needs.

The "smart buyer" strategy was evident in the now cancelled Jupiter Icy Moons Observer (JIMO) program. The mission had high technical risk due to the use of nuclear thermal propulsion, so an innovative organizational structure was formed which combined government and contractor teams in a collaborative fashion termed "co-design". The structure also made the government nuclear expertise available to industry by allowing half of the government laboratories to join the contractor bid teams, while the other half were reserved to work for the government buyer teams.

The niche expertise required to design around the nuclear power source meant that commercial companies designing alone would have had to spend significant time learning how to work with the source. By pairing government and industry, the learning time was reduced and the quality of tenders prepared increased (R. Taylor, 2006).

While it did not promote commonality as such, the JIMO mission illustrates that unique project structures are possible under the Federal Acquisition Regulations (FAR). No FAR waivers were necessary for this structure (R. Taylor, 2006).

Industry-wide strategies

Centralized Technology Development

An approach which was identified as leading to commonality in the defense sector is the use of centralized research and development. As an example, the Air Force Research Laboratories (AFRL) receive technology requests from Air Force personnel across the United States. As a central point, the AFRL is in a position to aggregate similar requests and develop technology which meets the needs of several groups within the Air Force. This leads to greater technology commonality than if the groups had requested technology development to meet their needs through separate requests to defense contractors.

Neutral Organization as Knowledge Repository

One avenue used by NASA and the DOD to improve commonality without compromising the intellectual property of contractors was the establishment of the Aerospace Corporation. One of its founding purposes was to serve as a repository on reliability data for satellite and launch vehicle components and systems. Aerospace Corporation would then apply this information to future government projects in a way that largely satisfied the contractors, but also preserved the knowledge of the US aerospace industry in general. Contractors have been willing to share information with the Aerospace Corporation because of its unique position as a not-for-profit, FFRDC organization with a charter that prohibits it from competing with contractors.

Contracting Strategies

Single Corporation as System Integrator

A conceptually simple way of increasing the chance of commonality being realized is to use a single contractor for two systems with significant commonality potential, and incentivize the contractor to seek out commonality.

In cases where commonality decreases up-front costs as well as long-term costs, a fixed cost contract can be sufficient incentive to realize commonality. One example is the NASA Fluids and Combustion Facility currently on the International Space Station. Through concept studies in the 1990s, independent contractors were responsible for two separate projects, the Fluids Facility and the Combustion Facility. At project inception in 1999, NASA combined the two into a single project office, and a contract was issued to a single contractor for both facilities under a fixed price contract. The commonality opportunities in the design and manufacture phases were so obvious to the customer that the corporation was sufficient to encourage some examination of commonality.

The Joint Strike Fighter discussed in detail by Boas is also an example of a single corporation acting as the system integrator. It is obvious from Boas' identification of the integrated management structure as a key factor in managing divergence that the level of commonality achieved by Lockheed Martin would have been very difficult to realize if each variant was designed by separate corporations.

One disadvantage of this structure is that it places large demands on the system integrator for large, complex systems. The system integrator must have a very detailed knowledge of the systems, attendant cost-performance trades, and stakeholder requirements. The system integrator must also have experience of the engineering difficulties associated with each of the systems. These resource demands are one reason why extrapolating this approach to a single system integrator for the entire Human Spaceflight Architecture is not straightforward. Further difficulties with this approach are discussed in Chapter 5.

Joint Ventures

Interviewees also commented on joint ventures as potential avenues to drive commonality into designs.

The prevailing opinion was that joint ventures are created due to skill asymmetry, rather than to drive commonality. For example, the Boeing-Bell joint venture created to beat Sikorsky for the technically demanding V-22 tilt rotor aircraft, or the joint venture between GE and Rolls Royce on the F136 engine, were both project joint ventures where the partners brought different skills to the table. GE and Rolls Royce had expertise in different but complementary areas and co-operating on this project was seen to be useful.

Interviewees were cautious about driving companies into joint ventures because it suited the perceived needs of the customer; rather they suggested allowing the market to develop suitable joint ventures based on carefully written requirements. However one exception to this strategy was found. On a project for the acquisition of night vision goggles, the Army considered four manufacturers (ITT, Litton, Varian and Vero Vellini) to be too many, and requested that two joint ventures were formed. Originally the commonality between the manufacturers was limited to the standard external interfaces specified by the Army. The joint ventures drove commonality internal to the goggles within the ITT-Vero team and within the Litton-Varian team.

One interviewee expressed the view that there are "soft" factors like cultural mismatches which can also cause joint ventures to fail. He pointed to the NPOESS shared weather satellites, essentially a joint venture between two government organizations, and suggested the project failed because the DOD and NASA cultures were simply too different.

In line with the general view held by interviewees that joint ventures were delicate arrangements that depended on many more factors than just customer convenience, Park & Russo (1996) cite a variety of sources which give joint venture failure rates of between 50% and 70%.

Directed Subcontracts

Using a common subcontractor to design a system to meet the same function across two projects will improve the potential for commonality. For example, a company contracted to produce the ECLS system for both an in-space habitat and a planetary lander is likely to look for design commonality between the two systems to reduce risk even if it is on a cost-plus contract.

Interviewees considered it possible, but dangerous, to try to specify particular subcontractors in a proposal. The government's control over the subcontractor is limited, because there is no privity of contract between the government and the subcontractor.[10] Ordinarily the prime contractor has the right to choose and control its subcontractors, and in the most general terms any removal of rights from a prime contractor will come at a contract price increase to the government.

Additionally, there is no assurance that a common subcontractor will lead to common subsystem design. First, the subcontractor operates at the direction of the prime contractor. The prime contractors, as system integrators, may choose to trade the resource envelope allotted to the common subcontractor in different ways on the two different projects and direct the subcontractor accordingly. Second, the performance requirements or resource constraints may actually be different between the two projects, and the subcontractor will optimize the system accordingly. Without any incentive for commonality in the prime contracts, the prime contractors are likely to require the common subcontractor to optimize in each instance to help meet the prime's design targets.

An often-cited example of a commonality failure is the "square peg in a round hole" uncommonality dramatically highlighted on the Apollo 13 mission. The film of the same name may have overdramatized the dialogue, but it neatly summarizes the popular incredulity at the lack of commonality: *"They take square cartridges. And the ones on the LM are round. Tell me this isn't a government operation."* (Broyles & Reinert, 1995).

In fact, the Command and Service Module (CSM) and the Lunar Module (LM) had a common subcontractor for the ECLS system, but the different requirements for the two vehicles drove an uncommon design.

The Command and Service Module (CSM) was developed by North American Aviation (now Boeing) and the Lunar Module (LM) was developed by a competitor Northrop Grumman. Hamilton Standard (as it then was) was the Environmental Conditioning and Life Support Systems (ECLSS) contractor for both the CSM and the LM. Apollo 13 infamously demonstrated that the lithium hydroxide canisters used to remove carbon dioxide were cylindrical in the LM and cubic in the CSM. The cubic design minimized the storage volume of the canisters, while the circular cross-section of the LM canisters minimized the pumping power required to drive carbon dioxide removal. The CSM, designed to support more people for longer, needed more canisters and therefore storage volume was the constraining resource. The paramount consideration for the LM design was weight, and the batteries which provided power were heavy. Presumably in an attempt to minimize power, and therefore weight, the cylindrical canisters were considered the

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[10] In some cases the government may enter into a side deed with particular subcontractors to establish the necessary privity of contract. However these are usually intended to give the government certain rights if the project fails, and are not usually appropriate for day-to-day management of the subcontractor.

preferred design. In this case the use of a common subcontractor did not lead to complete system commonality. However, a common technology and similar design was used. This enabled the unintended sparing, although in a more rudimentary way than might have been hoped for. It is possible therefore that despite the apparent lack of commonality the use of the common ECLSS subcontractor was one of several factors that saved the crew of Apollo 13.

Common subcontractors may also result without any stipulation because there are only a small number of subcontractors able to carry out the tasks. This is common on government aerospace projects. The subcontractor pool is first reduced because the administrative requirements on government contractors discourage some technically capable contractors from participating in government work (Scherer, 1964). Secondly, in some technically esoteric branches of the aerospace market, for example microgravity life-support or high-reliability, radiation-hardened computer chips, often there are few technically capable contractors to begin with and therefore the likelihood of a common subcontractor is high.

One interviewee provided a counterpoint to the idea of common subcontractors, suggesting that dialogue among the NASA community was a sufficient information sharing pathway when the number of technically competent experts is small. They gave the example of the Constellation ECLS system development across Orion, Altair and the Lunar Surface Systems. In this instance the small number of technical experts in the area meant there were strong personal relationships which led to strong communications channels. In the opinion of the interviewee, these channels were more important in driving technological commonality than having a common contractor. Such a method is likely to be less successful in driving design commonality because of the additional complexity in moving from technology demonstration to detailed design. A further possible reason why the channels on the NASA community side were effective here was that the development process in this instance was incremental, in that a technology demonstration contract would be let, and subsequently NASA would perform testing, then an additional contract for further development would be let. This kept the NASA workforce actively in the loop on the development process.

Government Furnished Equipment

An obvious pathway to transfer common systems is to supply them as "Government Furnished Equipment" (GFE) which was discussed in detail in Chapter 2.3. Under these arrangements, a contractor is not responsible for a portion of the final system because it will be supplied by the government. In some cases the government builds the GFE, in other cases a second contractor supplies the GFE to the government.

Interviewees were generally comfortable with the idea of GFE as a commonality mechanism. They commented that the approach requires a good initial understanding of the common system so that interfaces can be defined, resource envelopes allocated and simultaneous development made possible. Most often the contractor is not liable in any way for failures associated with the GFE which means that test planning needs to be carefully coordinated between the government and the contractor to ensure that the system as a whole is fully tested.

Pyrotechnic devices as GFE

The Constellation team looked at the possibility of using common pyrotechnic devices across the Constellation elements. The drivers which led to the pyrotechnic devices being identified were cost and reliability benefits from commonality and low performance sub-optimality from commonality because of low variations in the required performance between elements. The model for the acquisition of common pyrotechnic devices was to have NASA contract separately for the pyrotechnics and supply those to the contractor as GFE.

The downside to GFE was that the project office would be responsible for the logistics and integration of the pyrotechnic devices. This was not a responsibility that the project office wanted, and they would prefer for Orion and Altair to arrive fully prepared, with each prime contractor subcontracting separately for pyrotechnics. The cost savings associated with commonality were also small because of the low production volume. Therefore there was not a compelling, provable case for significant commonality benefit, and the GFE approach was not used.

Avionics

A GFE approach was also examined for common avionics between the Orion and Ares vehicles.[11] This had the potential for significant cost savings, as the most expensive line item in the Orion acquisition was software. A common avionics strategy was not pursued for several reasons. First, by the time the potential commonality was identified and investigated it was too late to capture all of the benefit of establishing a common avionics project. The Orion and Ares projects had been established prior to the overarching Constellation groups such as the commonality group. The project momentum was too great to cease work on the separate development projects and begin a common architecting approach. (Ironically, the lessons learned from the common architecting exercise may have been more valuable to any post-Constellation architecture and may have in fact resulted in less work being "lost".)

The team that worked the common avionics study believed that a separate project office was necessary for the workable acquisition of a common system. There would be "immense difficulty" in the contractor on one development project (eg Orion) trying to anticipate, negotiate and fairly evaluate the requirements of a second contractor's system (eg Ares).

The NASA commonality team also pointed out that the avionics industry was a higher clockspeed industry than the pyrotechnics industry. The offset between Orion and Ares development and Altair development meant that common avionics would be obsolete before they were acquired for all systems.

Contract Incentives

Many of the interviewees expressed the view that contract incentives were a necessary but insufficient condition for commonality development. One went as far as to say that it is not possible to use contract incentives to close a business case that is not otherwise compelling to a corporation. Most were reluctant to place significant contract incentive on a fixed level of commonality given the uncertainties around the optimum level of commonality.

One interviewee felt that commonality was such a nebulous concept that *any* contract incentive payment related to commonality would be "gamed" by a contractor and was essentially wasted incentive. Some support for this view came through examples of defense contracts given in the interviews where contractors were given incentive payments for "playing nice together": attending interface co-ordination meetings, raising interface issues promptly and similar tasks. The interviewee involved with the contracts stated that the contractor always did enough to get the maximum score (and therefore maximum revenue), but no more.

The interviewees noted that the additional revenue earned by developing a second independent project almost always outweighs the additional profit made by meeting incentives for fully developing commonality on the original project. Whether businesses maximize profit or revenue from a contract depends on market conditions as discussed above in Chapter 2.3. Therefore the

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[11] The Constellation commonality working group carried out a significant study on the potential for avionics commonality. The study was marked *sensitive but unclassified*, and was therefore unavailable to the author during the writing of this thesis. Those with access to the document may wish to read this case in more detail.

incentives for commonality need to be extremely strong to overcome the corporate predilection towards multiple development projects.

Contracts for services

Contracts for services are increasingly being used in place of the acquisition of hardware. Essentially, the contractor operates a product for the benefit of the customer rather than supplying a physical product for the customer to operate.

One example is the provision of aircraft engines under a system where the aircraft operator pays the engine maker per hour of engine operation, rather than purchasing the engine outright, an arrangement offered for many commercial aircraft and recently for the military tilt rotor the V22 Osprey. These "power by the hour" arrangements transfer responsibility for lifecycle costs to the engine manufacturer rather than the engine operator.

The contract for service strategy has been used in aerospace also. Hamilton Sundstrand built a Sabatier reactor to supply water on the International Space Station and are paid by the liter. The NASA Associate Administrator for Space Operations remarked *"[t]his is a fundamental shift in the way we do business... the contractor is responsible for all system development and performance. The only requirements we have imposed are those associated with safety and interfaces."* (Curie, 2008) The same economic effect can be seen in the United States' purchase of transportation services on the Soyuz launch vehicle instead of paying contractors to construct a launch vehicle which NASA would operate.[12]

These arrangements force the product manufacturer to make decisions based on the operating costs of the product as well as the up-front costs. This makes the contract for service particularly well suited to products with significant commonality potential because the commonality benefit is often most pronounced in the operating phase. One disadvantage of the strategy is that it requires competition (or some other price discovery method) to incentivize contractors to search for life-cycle cost savings and pass the savings through to the customer. The recent rise in Soyuz seat prices[13] is evidence that a contract for service is not guaranteed to reflect the true costs of operating the system without competition.

Develop and buy-in

A develop and buy-in strategy occurs when an initial project develops a potentially common system, and is then rewarded financially when future systems choose to use it. This is an extreme commonality strategy which tries to create a microcosm of a market economy within a NASA center. It goes further than the Goddard Common Flight Software case examined by Rhodes (2010), where projects paid a "tax" to use the common software which went to software maintenance. Under develop and buy-in, the original project is attempting to provide a more attractive option for the second project than independent development.

One interviewee with particular expertise on acquisition structures was asked about the viability of this type of strategy. That interviewee felt that it would be very challenging to implement and no other interviewee raised develop and buy-in as a potential mechanism for improving commonality.

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[12] More factors than simply acquisition strategy influence this choice. However the economic effect is that the Soyuz operators pay for the lifecycle cost of the vehicle.

[13] The price of Soyuz seats was $47 million per seat in 2008 ($141 million for 3 seats; NASA Contract Release C08-068) and rose to $63 million per seat in 2011 ($753 million for 12 seats; NASA Contract Release C11-013). The "space tourist" rate in 2007 was reportedly between $20 and $35 million per seat (Conlin, 2007).

Question Three: To what extent do Federal Government regulations and practices limit the acquisition strategies available for commonality?

NASA acquisitions are governed by both the formal requirements of the FAR and general acquisition practice. The FAR is theoretically open to the adoption of innovative acquisition strategies, but the practical realities of fixed yearly budgets and an inability to commit to purchases in future years or across centers eliminate some commercially viable commonality strategies.

Federal Acquisition Regulations

The interviews indicated that the FAR are moderately flexible and can accommodate a range of acquisition strategies other than the *"full and open competition"* which is the strategy required by default for acquisitions under the FAR (FAR section 6.101).

Sole sourcing can be justified if there was demonstrable advantage to selecting a particular contractor. One interviewee said that at a certain point in the acquisition process *"you need to stop changing horses"* and pursue a sole sourcing strategy. In a competitive award it is possible to take into account the effect on commonality when deciding to award a contract, even if this clearly favors a particular contractor (FAR section 6.302(1)). The test is whether the expected cost of switching to a different contractor outweighs the benefit expected from the competition.

Going further, some interviewees stated that waivers to aspects of the FAR were possible. While such waivers do exist, the waivers chiefly concern social policies implemented through the FAR, such as small business support. More extensive waivers in specific cases are possible by an Act of Congress but in practical terms such waivers amount to a change in law. The practical view of one interviewee was that the process of obtaining any waiver to the FAR was to be avoided because it was complex, time consuming and difficult. The interviewee felt that there was sufficient potential for innovation available within the FAR itself.

One interviewee indicated that the most important areas in managing commonality between contractors are not in the FAR; instead they are writing clear requirements and specifications, dealing with budgetary issues year by year and managing divergence.

Restrictions of the FAR in practice

The general support for the flexibility of the FAR contrasts with a perception that there are other constraints on government acquisition. Four hard constraints were repeatedly voiced by NASA project managers and acquisition officials.

First, spending above budget in a given year is not permitted even if it will decrease life cycle costs significantly, under the Antideficiency Act (Rendon & Snider, 2008). A NASA project manager must always fall within their allotted yearly budget, regardless of the impact in future years of under spending or investment in the current year. This means that commonality opportunities cannot be solely justified based on a "return on investment" mentality as in the private sector. A specific example was given of the Orbiting Carbon Observatory, where a $1 million over-budget spend request was denied although it was shown to offer savings of $8 million in the following year.

An alternative expression of this idea was put forward by an interviewee responsible for seeking out commonality opportunities in the Constellation program. The major question to ask in assessing commonality is: *"will common development give a lower total headcount for my project than independent development?"* If the answer is no, then obtaining approval for common development will be difficult. This approach means that many of the commonality benefits and detriments shown in Figure 8 are discounted.

Second, most government projects cannot use future years' funding to commit to current purchases, again as a result of the Antideficiency Act. This means that the economic benefits of promising larger production runs to suppliers due to commonality are largely lost, as the production runs cannot be firm until the year in which they are required to be ordered. Purchases for future year items can be made, and frequently are for long lead time items, however the current year budget must include the full cost of those items. This factor combines with the yearly budget cap noted in the previous paragraph to make multi-year bulk purchasing impractical.

Note that some projects are "fully funded", meaning their entire predicted cost is obligated in the first financial year of development, even though the project will not require the funds until future years. This ensures that the funds to develop a full end item will be available, and the project can be appropriately planned. "Fully funded" projects only run into budgetary trouble if their procurement extends longer than five years or exceeds the original budget.

Other projects are also approved by Congress as "Multiyear Procurement" projects, which means that funds are committed for future years' spending. This occurs most often when *"production risk is minimal and opportunities exist for economies of scale with a contract for a large quantity"* (Scherer, 1964). The requirement to obtain Congressional approval for multiyear procurement is a significant obstacle.

Third, there is often little incentive on behalf of the government project offices to spend less money, provided they remain within budget. Most often, funds cannot be carried over from year to year, with the unsurprising result that most government agencies spend all their budget, every year. To compound this difficulty, surplus funds in a given year may not be used to purchase items needed in future years (often referred to as the "bona fide needs" rule) (Rendon & Snider, 2008, p. 203). In a letter to acquisition professionals in the Department of Defense, Dr Ashton Carter stated as a ground for reform that services would be allowed to retain amounts they saved, implying that saving funds currently is not permitted (Carter, 2010, p. 3).

Finally, different NASA centers are not permitted to aggregate purchase orders made at the center level to increase purchase quantities. This eliminates up-front cost savings due to economies of scale and therefore reduces the immediate incentive to implement a common solution across centers.

One interviewee pointed out that these limitations become less severe if the acquisition can be thoroughly planned in advance. This requires steady requirements and budgets, as well as margin for schedule and budget slip.

Technical involvement in acquisition decision making at NASA

Within NASA, acquisition strategies are developed at the mission directorate level, and then passed to the procurement officials at NASA Headquarters for approval. The level at which the acquisition strategy is crafted is important because it affects the understanding that the acquisition planners have of the particular project requirements. For example, the acquisition structure for the JIMO project hinged on the technical risk issues associated with nuclear electric propulsion (NEP). An acquisition structure which failed to take this into account would have resulted in a much higher cost acquisition as contract teams priced in the risk of developing the NEP system. Several interviewees highlighted the need for adequate technical input into acquisition strategies at the outset and in making determinations of contractor progress during the project.

Effect of layers of oversight on acquisition decision making

The number of layers of oversight increases as the value of an acquisition increases. For example, at a certain level of spending, the office of the Secretary of Defense (OSD) will involve itself in briefings and decisions on projects. This oversight process may make it more difficult to obtain approval for innovative processes on very large projects, as it is more difficult to object to a by-the-book strategy than an untried one.

Commonality approaches in the Department of Defense

DOD 5000.2 is the DOD's equivalent of the FAR. Although DOD 5000.2 specifies the acquisition process in greater detail than the FAR, efficient acquisition is an increasing concern of the DOD and therefore defense contracting on major projects offers a source of ideas with which NASA can improve its acquisition structure.

Three current trends in DOD acquisition which may impact commonality were described by interviewees. There is increased emphasis on open architectures, more incentives to buy "commercial off-the-shelf" products and more specialization from contractors.

DOD increasingly requires open architectures, described as a *"shift from proprietary to public architectures"* (Rendon & Snider, 2008, p. 59). By definition an open architecture requires some commonality, either by defining common interfaces (closer to building block commonality), or by making open source designs widely available for adaptation by others (closer to reactive reuse).

Traditionally, DOD has promoted open competition as the best route to cost efficiency. One interviewee suggested that DOD's view may be changing. The growing alternative view is that unbridled competition in fact increases inefficiency and increased government direction in the specialization of preferred firms into particular development areas may reduce costs.

The third trend is increased use of commercially produced products. The DOD is increasingly open to buying them with a renewed emphasis on COTS parts over perfect performance. *"The Department recently prefers the use of more commercial, off-the shelf systems that provide more timely deliveries"* (Rendon & Snider, 2008, p. 185). One NASA example is the development of standard bus architectures from commercial suppliers for satellite projects by NASA's Rapid Spacecraft Development Office at Goddard Space Flight Center.

The selection of specialized companies, together with increased commonality from the manufacturer side, is likely to lead to more commonality in defense space projects. Commonality of course is not a goal in itself, so it is unfortunately too early to see whether these trends result in a more cost-effective strategy.

The DOD appears to place greater value on having fully funded acquisition programs than NASA. *"It has been a long-standing DOD policy to seek full funding of acquisition programs... Experience has shown that full funding is a necessary condition for program stability"* (Defense Acquisition University, 2011a, section 3.2.3). In contrast, the 2008 NASA procurement tenets do not mention the funding structure of acquisitions (Dale, 2008). This may be a result of the brevity of the 7 pages of NASA tenets compared with the voluminous Defense Acquisition Guidebook, however no interviewee from NASA or DOD mentioned obtaining full funding as an important way to manage the acquisition of a project.

Question Four: What types of NASA projects would benefit from an acquisition strategy focused on commonality?

High value projects in the early stages of development and facilities and ground support equipment are likely the best targets for commonality-focused acquisitions, but there were a wide variety of dissenting opinions.

Several interviewees expressed doubt that complex space architectures could benefit significantly from commonality. One interviewee opined that space projects exist to *"push the envelope"*, and that if there is substantial commonality *"we are doing something wrong"*. This view was prevalent among the project managers of smaller projects.

Constellation architectural commonality

The perspective of the Constellation commonality analysis teams was that the benefits of architectural commonality were significant, while the benefits of component level commonality were relatively minor. The cost savings associated with common components are limited by the small buy quantities in space projects. The Constellation commonality team estimated that the maximum cost savings that might be realized from common components was in the single digit millions. Generally this meant that the cost savings associated with the commonality were comparable to the costs of doing a study to determine whether the case was a suitable one for commonality, making it insufficient.

Facilities and Ground Support Equipment

Common facilities were identified by interviewees as a productive area for space project commonality. Examples include the common use of the Deep Space Network for spacecraft communication, or the creation of shared test-beds like the GRIP. Unfortunately, none of the examples examined had an interesting acquisition structure. A "complex algorithm" is used to share the operating cost of the DSN between the organizations which use it, however individual projects which propose to use the DSN treat it as an available no-cost resource. Their use of the DSN is a factor in evaluating their proposal. GRIP is a common testbed built as a separate project because it appeared that several projects would required a gravity testbed. GRIP is funded separately from the projects which use it.

Note that there is little flexibility in purchasing common ground equipment. An accounting perspective of cost sharing at one NASA facility identified only two approaches for the procurement of common ground support equipment. If the equipment was demonstrated to meet an anticipated common need then it could be purchased in advance with institutional (centralized) funds. On the other hand, equipment purchased for a single project would need to be paid for out of project funds, despite opportunities for other projects to utilize the equipment.

Question Five: Which factors drive commonality success?

Strong management leading to commonality success was a constant theme through interviews with project participants. Interviewees also pointed to the need for mandated commonality, clear examples of commonality benefit and the need for firm requirements.

A number of interviewees felt that commonality success was driven by the enthusiasm and personality of the person responsible for ensuring commonality. The first observation was that there should be a single person responsible for commonality. The second was that there will be resistance to the implementation of commonality at the individual project level and the commonality manager will need a strong and determined personality to override project-level resistance. The commonality manager also needs visibility across all current and potential variants and authority to force variants into a common approach, while avoiding the perception that the manager is biased toward a particular design.

A strategy which has worked in the past in driving projects to agree on common requirements is to mandate that the project must use the common developed solution. Faced with a choice between accepting a common solution into which they have no input, and one which they have some input, most projects will choose the second approach. Again, this requires strong leadership, and constant reevaluation, to avoid a situation like NPOESS (discussed above), where two organizations with very different cultures were forced into a commonality approach which did not work.

Several interviewees also pointed to a "tipping point" in commonality development. Often there was a clear example of where commonality was an obvious solution, delivering cost and schedule benefits. For example, on the Combustion and Fluids Facility the tipping point was the acquisition of common radiation hardened processors to achieve economies of scale and cost savings. This led to investigations of other areas where commonality could deliver savings.

Firm requirements were identified by several people as a key contributor to successful commonality. If items are contracted out under a fixed price contract, the requirements must be fully determined. Any requirements undefined at this stage will be priced into the contract at zero cost, and their cost recovered via a change order in future when the requirement is known. Effectively, according to one interviewee, the undefined requirement will be ignored by the contractor until it becomes more certain, because the full cost of the consequences of that uncertainty can be recovered.

An interesting footnote to the need for firm requirements was the insistence of one interviewee on function-based requirements as an important precursor to commonality. Function based requirements are appropriate for the situation where a single contractor is to maximize the commonality of their system, for example by designing a system for dual use. On the other hand, form-based requirements help to improve commonality across multiple contractors because two contractors will build to the same specification.

Question Six: What are the obstacles to inter-contractor commonality?

All interviewees expressed concerns about the difficulty of implementing extensive inter-contractor commonality. An overriding theme was the lack of positive incentive for companies to work together, coupled with significant downsides for companies which cooperated like loss of intellectual property or market leadership. Other obstacles were also identified, including disruption to supply chains, impacts on industry competitiveness, lack of incentive for design teams, late identification of commonality opportunities and aversion to sub-optimal performance.

One interviewee felt that commonality may disrupt existing supply chains or strategic alliances. He emphasized how in the aerospace industry, prime contractors and sub-contractors work together on multiple projects over years. Many project failures or cost over-runs are caused by cost breakdowns at the interfaces between the work packages of different organizations.[14] Inefficiencies in interfaces contribute to cost overruns because system integration can account for up to 40% of total costs (Rendon & Snider, 2008, p. 55). Allowing prime contractors to choose their teams and take responsibility for system integration provides a market force for developing good work processes between sub-contractors and contractors. Specifying particular GFE systems or mandating sub-contractors may dilute the market incentive on contractors and subcontractors to work most efficiently together. Component-level commonality through mandated suppliers also perturbs established supply chains, which may increase cost.

Many interviewees were cautious about commonality because it ran counter to the established method of competition for ensuring efficient pricing. Government acquisition officials want to ensure at least two healthy and competitive potential contractors for any contract, and commonality may threaten that corporate ecosystem by preferring one contractor over the other for all acquisitions. Acquisition strategies which carry two manufacturers throughout the acquisition in order to preserve competition deliberately sacrifice commonality and increase lifecycle logistics costs to decrease the unit cost. Examples of this strategy include the JTRS radios and the recently overturned approach of having two engines for the F-35 Joint Strike Fighter. Therefore the minimization of long term costs may require a lack of commonality.

Several interviewees pointed to a managerial or contractual disconnect in passing the system-of-system benefits of commonality through to the design team level. The design teams need to take certain actions at the sub-system level to ensure that commonality occurs at the system-of-system level, for example, accepting performance sub-optimality for the sake of commonality. However, often the design teams do not have visibility into the cost structure at the system-of-system level and therefore cannot see the system-of-system benefits, only the local detriment to their sub-system. This encourages divergence.

An example occurred with the development of the Constellation commonality plan. Commonality plans are an established way to develop and enforce architecture level commonality (Rhodes, 2010). The Constellation commonality plan was developed over a 12 month period between 2006 and 2007. The plan was seen by the Constellation project offices as an imposition of an additional reporting requirement, which resulted in a cost and schedule burden. This meant that the commonality plan was watered down each time it went to the project offices for review. There was little acceptance of the utility of the commonality plan, which became a self-fulfilling outcome. The plan was developed by a team of between three and five people, with additional technical experts participating on an as-needed basis.

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[14] One example discussed during the scoping interviews was Boeing's production of the 787, where many of the performance and schedule difficulties arose from interface issues between the contractors who made up the global supply chain.

Less rational objections to commonality were also identified during the interviews. People take "ownership" of designs which they have developed, and will often defend these designs passionately even within a company. Commonality implementation often involves choosing between two or more competing alternatives each of which people are invested in. This is particularly the case when commonality is woven into a system after some development has taken place. It is likely that the defense of variants from two different companies would be even more hostile. On the NASA Combustion and Fluids Facility installed on the International Space Station, the ownership sentiment was very strong at the outset of the commonality exercise. It was overcome using rational demonstrations of commonality benefit based on agreed metrics like cost and reliability, and strong leadership.

A clear obstacle to commonality for one interviewee was the lack of leadership support for up-front identification of commonality opportunities. The avionics and pyrotechnics commonality studies for Constellation would have been more favorable towards commonality if the design process had been less advanced at the time of the commonality study.

Interviewees were curiously divided on whether the negative performance impact of commonality was a significant obstacle. To some, the cultural shift in NASA required to design for sub-optimal performance was a key reason for the uninspiring results from commonality to date. DOD perspectives held that many of the joint projects that failed did so because the organizations sponsoring the different variants could not agree on a compromise between their sets of requirements. In contrast, some interviewees felt that the performance-cost trade was simply a part of engineering design, and with an engaged customer and properly written requirements, contractors could deliver solutions at any point along the performance-cost spectrum.

Summary

The results of the scoping interviews discussed in this chapter are summarized in Table 9. Another key outcome of the scoping interviews was shaping the detailed case studies examined in this thesis. The detailed cases on the JTRS radio development and two commercial launch providers will be discussed in the next chapter.

CHAPTER 4: DETAILED CASE STUDIES

The scoping interviews described in the previous chapter provided a broad introduction to the issues that affect commonality in government acquisitions. The following case studies of military radios and launch vehicles delve into particular commonality projects in more detail. Each is intended to provide deeper insight into the problem of government acquisition of common systems than could be achieved from the short scoping discussions.

4.1 JTRS COMMON SOFTWARE CASE STUDY

Introduction

This section 4.1 will discuss the first of the detailed case studies, the Joint Tactical Radio System (JTRS) developed by the Department of Defense (DOD). In aiming for an affordable and interoperable system of radios, the DOD tried to share common software between different radios with mixed success. This case study is important for two reasons. It captures acquisition behavior from the government perspective, unlike the two commercial organizations examined in the subsequent case studies, and it offers insight into software commonality, which is valuable given the climbing contribution of software to project costs.

Although there were several aspects to the acquisition strategies used in JTRS, this case study will focus on the attempt to make the JTRS software common across radios. The case study will briefly outline the objectives of JTRS and provide a technical overview. Then the benefits and drawbacks of commonality as seen by DOD will be examined. Against this background, the commonality strategy, management structure, funding structure and acquisition strategy will be discussed.

JTRS Objective

The objective of JTRS is to develop communications systems that are interoperable between friendly warfighters, whether pilots, ground troops, armored vehicles or navy ships. The communications systems are intended to provide data and video as well as voice communication. The network over which the communication takes place is intended to be open to any friendly forces in need of information, allowing warfighters to join a network and share information as needed. At the same time, the information must be secure, meaning it is accessible only to those with permission to do so.

The sheer number of radios required for the JTRS project means it will be gradually phased into service. Therefore JTRS must also be able to communicate with US and allied forces using pre-JTRS radios, referred to as "legacy" radios. As an example some JTRS radios include "Link 16", the current NATO standard for inter-operable air communications, in their communications suite.

A completely common radio was not a feasible solution because it could not cope with the different environments, constraints and missions required across the DOD. The 1997 Mission Needs Statement requires that *"to respond to variations in operating ranges and conditions, the system will need to operate over multiple frequency bands and with a variety of waveforms."* However, the need for interoperability plus the perceived similarity in the needs of the different services led to the formation of a joint project to *"bring together separate service-led programs into a joint software-defined radio development effort"* (General Accounting Office, 2003).

Technical description of JTRS

In a software defined radio (SDR), simple radio hardware is controlled by complex software. Changing the software causes the hardware to perform differently. Several sets of software can be pre-loaded onto the SDR and it is the type of software selected, rather than the hardware, which controls the output of the radio.

There are two major advantages to an SDR over a conventional radio where fixed hardware provides fixed performance.

First, a single set of hardware can be used to communicate with a range of other friendly units, each of which may be using a different radio. Without an SDR, achieving this level of communication between units would require carrying multiple sets of radio hardware. A single set of hardware leads to weight and volume savings. It may also lead to affordability savings due to the lower number of units purchased, provided the unit price of the software defined radio was still relatively low. As an example, US infantry may be using SINGCARS radios, NATO armor may be using LINK 16 and recently upgraded special forces may be using the Soldier Radio Waveform (SRW). A US aircraft would ideally be able to communicate with any of these units. A pure hardware solution would require the aircraft to carry three different radios to communicate with the three different forces. A software defined solution in contrast would only require the aircraft to carry a single piece of radio hardware running three different software packages.

As a second advantage, an SDR can be upgraded more quickly and easily to reflect changes in operations. The design of any radio is a trade-off between factors which often compete, such as signal strength, cryptographic strength, throughput and range. An SDR can load new software on existing hardware to change the trade-off if the operational environment changes. For example, if the aircraft above was deployed to an environment with heavy jamming, the waveform could be modified to make it less susceptible to jamming.

Despite this flexibility, there are still limitations imposed by the hardware. For example, the upper limit on the frequency of transmission by a JTR Set is 2GHz. Software patches cannot change this. This limitation is becoming restrictive as feeds above 2GHz are required for video communication with UAVs (Button, 2010).

In order to understand the difficulties DOD encountered when attempting to implement commonality of software across the JTRS family of radios, it is necessary to understand the architecture of the JTRS in more detail.

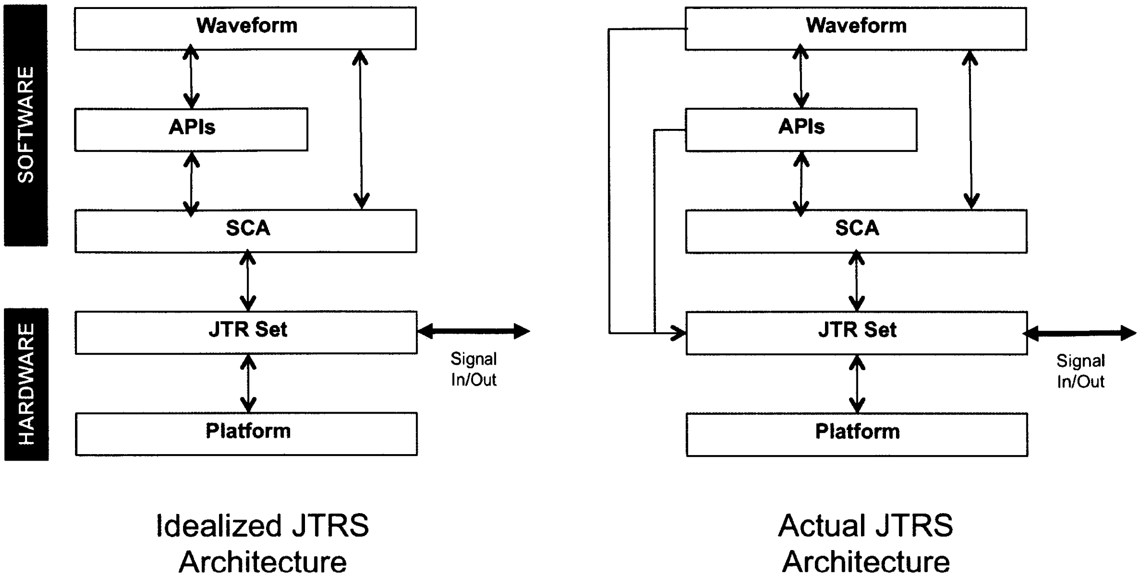

Figure 41: Idealized and Actual JTRS Architectures

There are five elements to the JTRS architecture, shown in Figure 41:

1. **A set of "platform services".** A platform[15] is the warfighting element the radio will be integrated with. The platform could be an infantry commander's laptop, or the electronic systems of an airplane or navy ship. The platform provides the interfaces with the human operating the system and must be able to communicate with the JTRS software. The platform hardware must be physically interfaced with the JTRS hardware layer.
2. **A hardware layer ("JTR Set").** The JTRS hardware layer includes RF components like antennas, transmitters and receivers, associated circuitry and processors to provide low level control of the RF circuits. Critically, some of the RF hardware is software-tunable. This hardware box is referred to as the "JTR set" for consistency with the DOD terminology. The physical configuration of the radio in terms of size and weight is referred to as the "form factor". Table 10 shows how the JTR sets were grouped into "clusters" based on their intended platform. The clusters formed the basis for acquisition partitioning.
3. **A software interface layer ("SCA").** The "Software Communications Architecture" (SCA) layer is meant as a *"core framework for software applications to operate on different JTRS platforms"* (GAO 2003).
4. **Standard software programs ("APIs").** "Application Program Interfaces" (APIs), are small programs that control various aspects of the hardware, and which may be used by the waveform layer in implementing a waveform.
5. **The radio waveform layer ("Waveform").** The waveform is pure software. It controls how the JTR set packages data, which modulation format is used, how data is encrypted and the frequency and bandwidth at which the data should be transmitted. Ideally, the radio waveform only interfaces with the APIs and the SCA.

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[15] The term "platform" comes from the Department of Defense lexicon and means a warfighting element such as an airplane or tank. It does not overlap with the way "platform" and "platforming" were defined in the commonality context in Chapter 2.3.

Table 10: JTRS Hardware Types (adapted from Feickert (2005))

Summary of JTRS Hardware Types						
JTR Set	GMR (Ground Mobile Radios)	CISHR – JEM	AMF (Airborne, Maritime, Fixed)		HMS (Handheld, Manpack, Small Form Factor)	MIDS – JTRS
Cluster	One	Two	Three	Four	Five	Not applicable
Description	Ground, Vehicle and Helicopter Radios	Hand-Held Radios	Fixed Site and Maritime Radios	High Performance Aircraft Radios	Handheld, Dismounted and Small Form Factor Radios	Aircraft replacement for MIDS – LVT
Original Service Lead	Army	Special Operations Command	Navy	Air Force	Army	Air Force
New Dev't or Upgrade?	Complete New JTRS Developments					Upgrade of MIDS to JTRS

The form factor of the hardware layer was determined by the physical platform on which it would be used. Different platforms have varied sensitivity to the size, weight and power-draw of the JTR Set.

The form of the software (SCA, APIs and Waveform) was intended to be independent of the physical platform. Each of the JTR Sets would in theory run the same hardware-independent waveform. This decoupling would have reduced the complexity in the system, and allowed common waveforms to be used across all the systems.

However there was in fact coupling between waveforms, JTR Sets and platforms. First, the more waveforms, and the more complex the waveforms, intended to run on a particular hardware set, the more power the set consumed during operation. Greater power consumption required a larger volume and mass for adequate heat dissipation. This meant that small JTR Sets such as those attached to remote ordinance or carried by infantry could not run a large number of different waveforms, and required more efficient operation from those waveforms that were run.

The properties of the physical platform also affected the types of waveforms which were appropriate to run on the platform. Specialist waveforms had to be developed for specialist applications. For example, fast moving aircraft which used the AMF JTR Sets and the MIDS-JTRS JTR Sets are more likely to lose parts of the signal, and therefore require more repetition of information to transmit a message. This led to the development a specialized waveform for aircraft.

Commonality strategy

The JTRS commonality strategy was closely connected to the way in which the architecture was defined. The waveforms, APIs and SCA were intended to be common. The JTR Sets and platform integration were not.

Software, the focus of this chapter, was intended to be common across the different JTR Sets. As waveforms were developed, they were intended to be effortlessly portable to all JTR Sets. The

2003 GAO presentation on JTRS summarized the early thinking on software commonality, presciently placing it under the heading "technical challenges": *"Portability: Ensuring waveform and other software capabilities are available to all JTR sets in "plug and play" format."* The SCA was intended to be common across all architectures regardless of platform or waveform. The SCA was the keystone into which both hardware and software integrated, and any changes to the SCA would have far reaching impacts.

Initial hardware commonality strategies (Army Supportability Assessment 2003) were quickly abandoned. There was no program-wide intention or strategy for common components or hardware. Each hardware manufacturer would develop hardware based on the unique form requirements of the particular platform.

The vision of absolute software commonality, however did not emerge. A 2008 paper (Stephens et al) wrote:

> *"...the end product of JTRS waveform development is not a binary software application. Instead, the end product is a set of source files that, with minimal changes, can be compiled and linked into a waveform capable of being hosted on a number of different platforms, along with the supporting documentation necessary to enable a third-party to port and optimize the waveform for a specified platform."*

In other words, divergence occurred. The goal was no longer common software (a common building block strategy) but portable software (closer to a reuse strategy). The causes of divergence will be examined later in this chapter, but first an examination of the benefits and drawbacks expected from the JTRS software commonality will be undertaken.

Perceived benefits of JTRS software commonality

The common software architecture was one of the key planks of the JTRS affordability strategy. In 2009, the JTRS "Waveform Portability Guidelines" stated:

> *"The portability of the waveform software across multiple JTR platforms is necessary for the JTRS Program to achieve the following goals:*
>
> - *Reduced cost through maximized reuse of waveform software across multiple platforms*
> - *Faster insertion of new technologies*
> - *Interoperability of radio systems between services*
> - *Reduced training requirements due to commonality of platforms"*

The key benefits sought from JTRS commonality were affordability throughout the lifecycle and interoperability.

Perceived drawbacks of JTRS software commonality

The public announcements emphasizing the benefits of JTRS commonality unsurprisingly did not mention the drawbacks to the commonality. Some of these drawbacks were identified by interviewees with hindsight, however the impression given by the interviewees was that there was an emphasis on commonality benefit early and a late realization of the drawbacks of commonality.

The most commonly noted drawback of JTRS commonality by interviewees was that technology developments in communications occur so swiftly that common architectures which take some time to implement are outdated before they reach full service. For example, the use of full video from UAVs has increased dramatically since the late 1990s when the JTRS architecture was first developed. This has led to alternative communication approaches which can accommodate frequencies above 2 GHz being used for UAV communication (Button, 2010). This drawback was noted only in interviews and GAO oversight reports and was not found in any of the discussions from the early 2000s on the benefits of JTRS.

The second drawback of commonality is the performance compromise entailed by software. Again, this drawback does not appear to have been widely recognized early in development. To preserve commonality, additional layers of software need to be added between the hardware and the waveform software. These additional layers slow the performance of the radio. Stephens et al comment: "S*trategies such as hardware abstraction layers can reduce the coupling [between hardware and software], but at the [performance] cost of increased delay and variability*" (Stephens, R. Anderson, Jimenez, & L. Anderson, 2008). Striking a balance between performance and commonality proved difficult.

Management structure

The management and funding of JTRS is closely tied to the way in which the acquisition was conducted, and had significant impacts on the realized commonality. The management structure for JTRS changed through its lifecycle to reflect learning on the best way to implement a common complex system.

The initial structure was a Joint Program Office (JPO) funded by the services, with each service taking the lead on particular "clusters" of JTR Sets. There was a profusion of working groups, multiple chains of authority (see Figure 42) and fragmented responsibilities (see the range of service leads in Table 10). The JPO was responsible for developing the architecture, managing waveform acquisition and certifying completed JTRS hardware. Individual services were responsible for acquiring JTR Sets to meet their needs, and integrating those radios with the platforms they were to be used on. The services were also responsible for the ongoing maintenance and support of those radios.

The 2003 GAO report heavily criticized this management structure: *"the most significant challenge we identified is the lack of a strong, joint-management structure"*. Despite the idea of a joint structure, the Army was effectively in charge, and this led to a bias in the joint development toward army needs: *"Army, as the service acquisition executive, has greater clout over requirements determination than other services"* (General Accounting Office, 2003). The report also recommended that the JPO be given acquisition responsibilities, however the DOD disagreed and acquisition responsibility remained with the services.

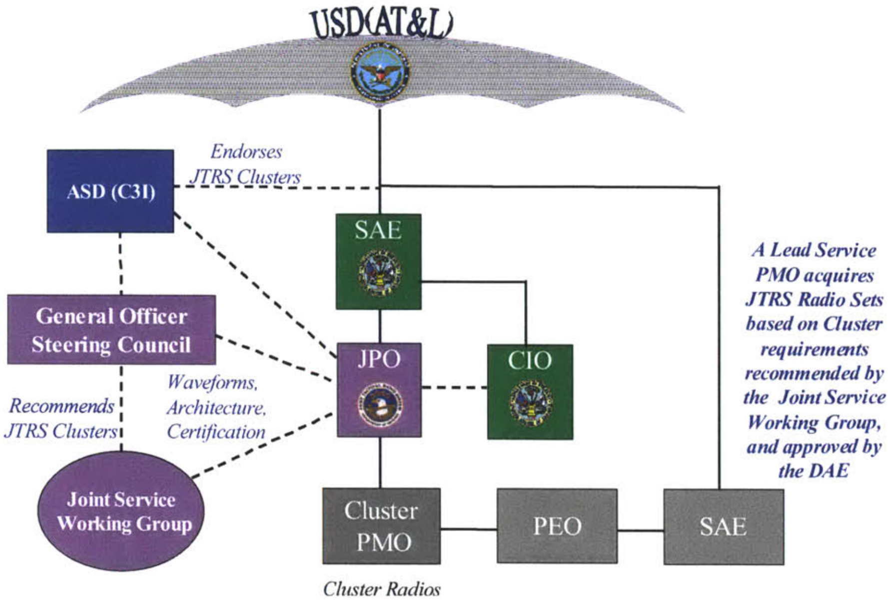

Figure 42: JTRS Management Structure (GAO 2003)

In 2005, the management structure was changed. The governance of the JPO became more streamlined and more powerful. The following quote summarizes the changes: *"Joint is difficult. We came back with a recommendation to adopt a corporate model where we have a board of directors. The board of directors is chaired by USD (AT&L) and the vice chairman of the Joint Chiefs of Staff…The beauty is that you have everybody in the room needed to make and enforce a decision."* (US Navy, 2008). The improved decision making framework was important in managing the common software.

JTRS Acquisition Strategy

With the foregoing technical and management background, it is now possible to discuss the way in which the JTRS was acquired.

The acquisition began with requirements definition and negotiation between the services in the late 1990s. The first aspect of the acquisition where corporations were involved was the definition of the SCA. The SCA design was led by the government, but included contractors and communications system experts also. The bulk of the architecture definition was undertaken in this forum where most contractors participated voluntarily.

Several interviewees commented that it may not have been advantageous to allow contractor experts wide freedom in scoping the SCA. There was little incentive for potential JTRS contractors on JTRS to develop a perfect SCA. In the first place, common software meant fewer future development projects than independent development. Even a partially hardware dependent architecture meant work porting partially common waveforms between variants. Secondly, contractors were keen to move to the development phase as quickly as possible because revenues and profits were much higher in that stage than the meager consulting fees for architectural definition. Finally, the open nature of the architecture definition meant that any technical insight that companies thought might present a technical advantage in procurement would not be revealed.

After the architecture was largely in place, it was possible to let contracts for waveform and hardware development. Table 11 presents a breakdown of the companies involved in the hardware and software acquisition and their roles.

Table 11: Selection of contractors involved in JTRS Acquisition

Organization	Hardware	Software	Major Subcontractors
JTRS HARDWARE DEVELOPMENT PROJECTS			
Boeing	GMR / Cluster 1	Wideband Networking Waveform	Northrop Grumman Rockwell Collins BAE Systems Harris
Lockheed Martin	AMF / (Clusters 3 and 4)	Link 16 (porting)	BAE Systems General Dynamics Raytheon Northrop Grumman
General Dynamics	HMS / (Cluster 5)		BAE Systems Rockwell Collins Thales
Datalink Solutions (DLS) (JV between Rockwell Collins and BAE Systems)	MIDS-JTRS		MIDS JTRS joint development between ViaSat and DLS
ViaSat	MIDS-JTRS		
JTRS SOFTWARE DEVELOPMENT PROJECTS			
ITT		Soldier Radio Waveform	
Assurance Technology Corporation		SINCGARS (porting)	
STOPGAP MEASURES FOR CURRENT WARFIGHTING			
Thales	CISHR – JEM / (Cluster 2)	(interim solution, not fully JTRS compatible)	
ITT	CISHR - Soldier Radio		
Harris	CISHR - Falcon III		

Subcontractors encouraged competition

Table 11 shows clearly that most developments have a prime contractor and several large subcontractors. This occurs both because the projects are large and complex and because the government encouraged leader-follower contracts during acquisition. For example, the content of the acquisition strategy for the cluster 1 radios went beyond simple development. Boeing had to qualify its subcontractors as manufacturers. *"DOD has emphasized competitiveness in contract awards to address affordability. Cluster 1 prime contractor is responsible for qualifying two subcontractors to develop and build Cluster 1 JTRS radios"* (General Accounting Office, 2003). The subcontract awards were made in such a way that there was price competition between the manufacturers, with the superior manufacturers obtaining larger shares of the production contracts. On the acquisition of the CISHR, where both Harris and Thales are producing acceptable variants, each receives production orders in a year based on its quality and value.

Prime contractors were likely to retain work in-house

The second clear point from Table 11 is that many subcontractors have multiple roles. For example, Northrop Grumman, Thales, General Dynamics, BAE Systems and Rockwell Collins are involved in multiple projects. This is not the usual case of a "common subcontractor" because in at least the case of Northrop Grumman and BAE Systems the functional area the companies worked on was different between the projects. The use of competitors as subcontractors encouraged the prime contractors to keep work in-house for fear of giving their subcontractors a competitive advantage. In the opinion of interviewees, this occurred even when the subcontractors were better qualified to take on the work.

One counter example to this uncooperative approach was noted. On the MIDS-JTRS contracts, DLS and ViaSat jointly developed the JTRS upgrade, but subsequently compete for orders. Figure 43 shows how the MIDS upgrade to JTRS is being developed very closely between DLS and ViaSat (Kim, 2009). Several interviewees stated that in instances where there were difficult technical problems to be solved, DLS and ViaSat cooperated to find the best solution on development. Their hypothesis for this unusual cooperation was that there was sufficient work in the industry to keep both in business, so long as there were no new entrants. The cooperation strategy between DLS and ViaSat seemed intended to maintain their joint lead over the competition in the MIDS strand of JTRS.

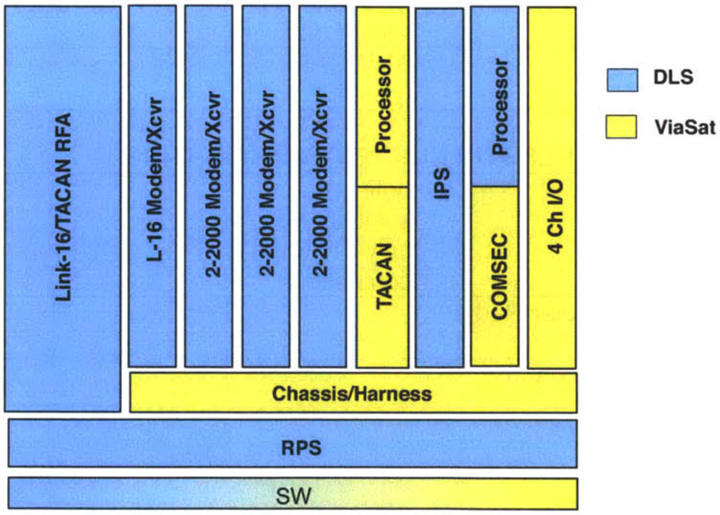

Figure 43: MIDS-JTRS was developed by both DLS and ViaSat (Kim 2009)

Development of both hardware and software by the same corporation decreased commonality

The third point which is clear from the data in Table 11 is that the Boeing Cluster 1 acquisition developed both new JTRS hardware and new JTRS waveforms. It was the first contract to be awarded. Both hardware and software were awarded to the same team because the program office was eager to have a working radio and waveform to demonstrate and coupling the hardware and software to a single team appeared to offer lower development risk. Also, the government was unwilling to assume the administrative burden of coordinating and integrating the hardware and software systems.

Unfortunately, this approach was counterproductive to making the waveform common. In order to speed development and increase performance, the Cluster 1 team worked around the edges of the SCA and created dependence between the JTR Set and the waveform as shown on the right hand side of Figure 41. For example, the waveform became dependent on whether the processing architecture onboard the JTR Set was FPGA[16] based or DSP[17] based. While the core of the problem was an insufficiently specific SCA, permitting a single organization to develop both the JTR Set and the Waveform under time and performance pressure contributed, because it incentivized the Boeing team to improve performance by coupling hardware and software.

This example reinforces Boas' recommendation that common building blocks be developed by separate contractors from those developing the projects they will be integrated into (Boas 2008). The simultaneous development of common software and unique hardware led to dependencies of the common software on the unique hardware.

Planned commonality decreased

There was also a decrease in the commonality of the waveforms across different JTR Sets as the acquisition progressed. Figure 44 shows the theoretical conception of JTRS early in the program (Bailey, 2008). Figure 45 shows the actual interaction between waveforms (across the top) and JTR Sets (in the first column) (North, Browne, & Schiavone, 2006). The reason for the change was that a block upgrade strategy was implemented in 2005 to keep the program within schedule and cost caps. There was *"roughly a 1/3 reduction in requirements"* between 2003 and 2006 (North et al., 2006). This resulted in less interoperability between JTR sets than originally intended, but enabled quicker delivery of some performance.

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[16] Field Programmable Gate Array

[17] Digital Signal Processor

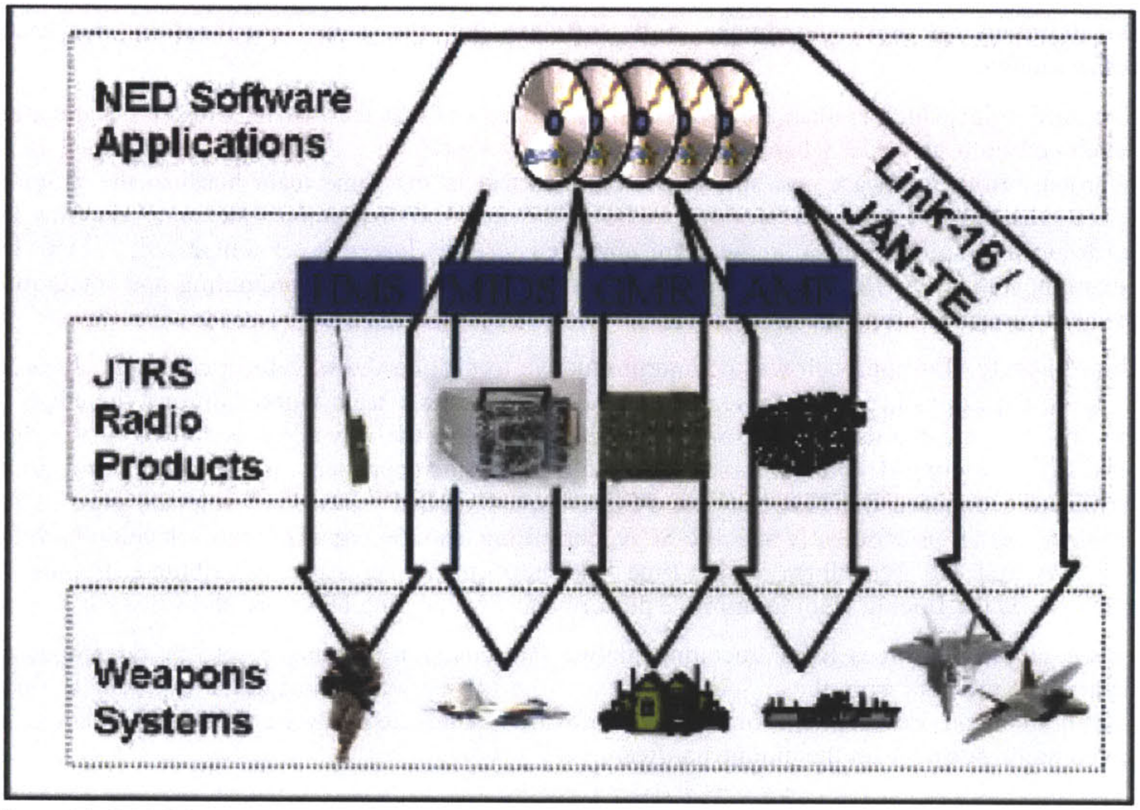
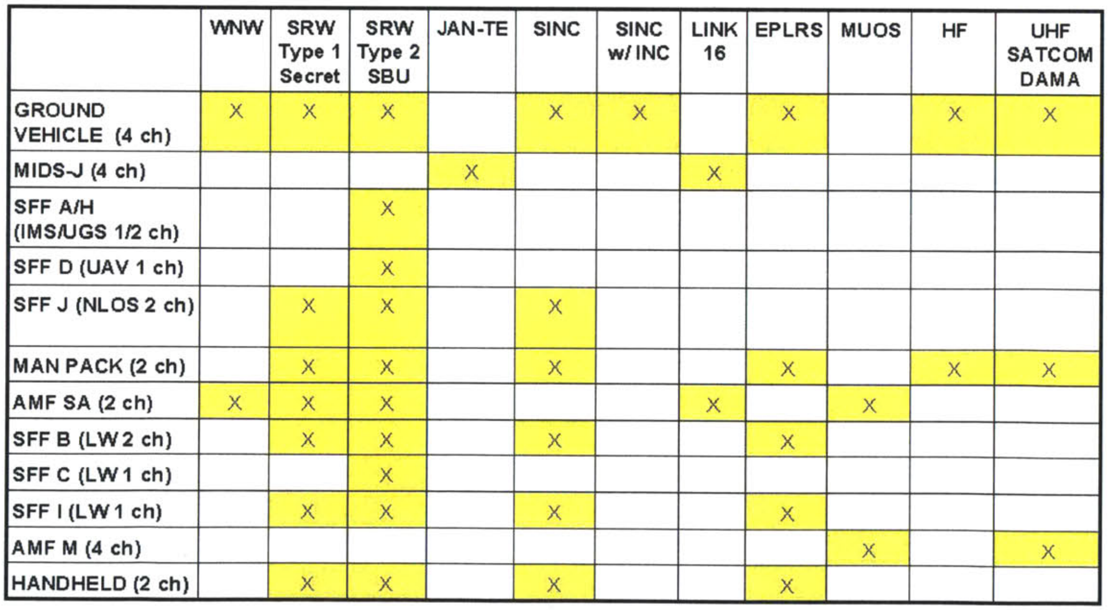


Figure 44: Initial Conception of High Waveform Commonality (Bailey, 2008)



	WNW	SRW Type 1 Secret	SRW Type 2 SBU	JAN-TE	SINC	SINC w/ INC	LINK 16	EPLRS	MUOS	HF	UHF SATCOM DAMA
GROUND VEHICLE (4 ch)	X	X	X		X	X		X		X	X
MIDS-J (4 ch)				X			X				
SFF A/H (IMS/UGS 1/2 ch)			X								
SFF D (UAV 1 ch)			X								
SFF J (NLOS 2 ch)		X	X		X						
MAN PACK (2 ch)		X	X		X			X		X	X
AMF SA (2 ch)	X	X	X				X		X		
SFF B (LW 2 ch)		X	X		X			X			
SFF C (LW 1 ch)			X								
SFF I (LW 1 ch)		X	X		X			X			
AMF M (4 ch)									X		X
HANDHELD (2 ch)		X	X		X			X			

Figure 45: Realized Commonality Was Lower Than Planned Commonality (North, Browne and Schiavone, 2006)

Making the common waveforms open led to divergence

An important part of the acquisition strategy was the waveform "Information Repository". The repository contained waveform software, which was open to any manufacturer who wished to develop a new JTRS-compatible radio. One stipulation was that *"any company that checks out a waveform from the JTRS Information Repository must return the modified or improved waveform back to the repository so future users can take advantage of those modifications"* (Rosenberg, 2010).

Unfortunately, because of the hardware-software coupling described above, waveforms often had to be modified by the hardware developer. For example, waveforms written for an FPGA architecture would not work on a DSP architecture. When the waveform was returned to the repository, it was difficult to identify which changes were actual improvements and which were mere modifications to make it work on the new software. Version control also became a time-consuming task for the managers of the repository.

In this respect, making the common aspects of the architecture open encouraged divergence. At the same time, making the architecture open encouraged reuse that might not otherwise have occurred. There was a trade between preserving perfect commonality which was unused, and allowing some divergence to encourage reuse.

Acquisition strategy was affected by unplanned policy changes

The open information repository strategy was accelerated when unplanned policy changes affected the acquisition strategy. The initial acquisition strategy was formulated in the late 1990s, but the acquisition needs of the DoD rose sharply with sustained combat operations in the mid 2000s. This placed the DoD in a difficult position. It needed to deliver radios to the warfighters who required them, but the JTRS radios were not yet ready. It could supply legacy radios, but equipping teams with legacy radios likely to last a decade or more would diminish the production runs of the JTRS radios when they became available.

The solution was to let *"manufacturers outside JTRS programs of record borrow waveforms from the repository and develop JTRS- compatible radios without the time and development costs typically associated with programs of record"* (Rosenberg, 2010). Several interviewees expressed the opinion that Harris's development of the Falcon III occurred far more rapidly than would have been possible under a government acquisition structure.

An additional contributor to the rise in contractor-funded development of radios was the edict from OSD that no service was to buy new non-JTRS radios without a waiver from OSD. Some interviewees suggested this waiver process was effective in allowing companies to build a business case for investing in the development of JTRS radios. Others stated that so many waivers were issued under the contract that the volumes of JTRS radios required by the services have significantly declined. Both points of view may be right, in that the policy's existence encouraged a business case which was undermined by the policy implementation.

This facet of the JTRS acquisition highlights the interaction between unplanned events and their associated policy changes on the one hand and the acquisition strategy on the other. It also shows that making common building blocks freely available encourages new entrants.

Contract types

One of the development contracts illustrated the weakness in using award fees to incentivize contractors. The Boeing team were on a cost plus award fee contract. However, for a variety of reasons the project went badly. The Boeing team reached a point of poor performance where it was impossible to turn the project around and achieve any of the targets for award fees. At that point, the incentive ceased to operate effectively.

Intellectual Property

The JTRS program realized early that the architecture and operating system must be *"Open and government owned"* with *"no proprietary information"* (Badolato, 1998). Unfortunately, this did not materialize in practice. The key obstacle was proprietary information in the low level software code which communicates with the hardware. By allowing the hardware to be open to any developers, some of the software required to run the hardware was by necessity proprietary. When this software needed to be included within the JTRS information repository, which was supposed to be completely open, it created significant difficulties. Allowing other contractors to access existing waveforms was not easy, and the portability benefits of the waveforms were almost lost. It appears that the solution was to negotiate on a case by case basis with each of the owners of the proprietary information. In some cases the outcome was that information could be released only to a limited range of people within the government. This hampered attempts by the government to encourage commonality by sharing information about the products being developed. The situation could likely have been avoided with a better early recognition of the detail of the proprietary information likely to be included.

Competition in acquisition was preferred to commonality in logistics at high volumes

The services remain responsible for integration, operation and logistics of the JTR Sets which they purchase. This creates a tension between acquiring a single type of radio from one manufacturer (giving logistics and sparing benefits) or acquiring radios from two different companies (giving competitive benefits and possibly a lower acquisition cost, but higher life cycle costs). The services were free to decide which of these acquisition approaches were preferred for that service's JTR Sets. For low value, high volume hardware, there is *"a much bigger payoff from the savings in the acquisition compared to the logistics tail. Single channel handhelds now cost less than $3,000. Many times it isn't economically viable to fix them. If we were talking about the Joint Strike Fighter, we would not want to sustain two different aircraft models, but in our radio world, we believe the business case is there to consume them"* (Program Executive Officer Bauman, quoted in US Navy (2008).)

Summary of Findings on JTRS Common Software Acquisition

Findings on inter-contractor behavior

Prime contractors may refuse to pass through work to better qualified subcontractors to avoid giving their subcontractors experience.

Information sharing between contractors is minimal when contractors will compete for follow on hardware contracts. However, the "cooperative competition" exhibited by DLS and ViaSat on the MIDS-LVT is a counter-example.

Findings on contracting strategies

Continuous competition works well in high quantity production such as JTRS. Several interviewees suggested it was not likely to be successful in lower rate production.

Cost plus award fee structures can lose incentive value when a contractor is so far behind on development that there is no chance of recovering any award fee.

Intellectual property

Intellectual property is a significant barrier to establishing commonality across the work of different contractors.

A negotiated intellectual property clause often places significant limits on what the information can be used for, because the Government must sign a non-disclosure agreement that makes it difficult to share the information.

Findings on joint architecture development between contractors

Contractors have a three pronged disincentive to ensure that any interface standard is comprehensive and fully thought through prior to starting production:

- The contractors will earn more profit during the subsequent hardware and software development phase, so there is an incentive to move to that phase as quickly as possible;
- A common architecture means less work in porting waveforms between variants for the contractors;
- Any architectural suggestions which require the contractor to share proprietary information are unlikely to be made, especially when competitive bidding follows the architecture development phase.

Findings on software commonality

A static interface architecture alone is insufficient to ensure hardware or software commonality.

Software commonality needs more attention to version control as a method of divergence management than hardware commonality. This is especially the case when contractors are meant to make both bug fixes and application-specific improvements.

Software commonality on different hardware platforms has an associated performance penalty.

4.2 CASE STUDY 2: COMMERCIAL LAUNCH VEHICLES

Introduction

The second case study examined a launch vehicle manufacturer ("**CS2**") with both commercial and government customers including NASA.

There were two separate lines of inquiry pursued in this case study:

7. Did CS2 **in its role as a system integrator** encourage and manage commonality among its subcontractors? If so, how? And if not, why not?
8. Was CS2, **in its role as a NASA or DOD contractor**, involved in projects with attempted commonality coordination among contractors? What worked well?

The first question was intended to assess industry practice in infusing commonality into the supply chain. New methods used here could be evaluated for applicability in NASA's exploration architectures. The second question was intended to give insight into the practicality of proposed NASA commonality strategies from the perspective of a contractor which would potentially work under the new acquisition strategies.

CS2's Products and Business Strategy

CS2 provides space launch services based on a family of launch vehicles with commonality. CS2 also produces bespoke vehicles based on this family to meet particular customer needs.

CS2 develops its vehicles with an extensive network of subcontractors, and views its role as a system integrator: it coordinates the subcontractors and undertakes system engineering, integration and reliability testing. CS2 produces a small number of systems in-house where it has particular expertise, avionics being the most sophisticated of these.

CS2's Commonality Strategy

CS2 runs a common system program ("**CSP**") which encompasses both hardware and software. Certain systems which are identified as common across most or all launch vehicles are managed by a common system group. The CSP is independent of any one launch vehicle development team and is instead matrixed across all development teams.

Each launch vehicle can be seen as a set of common systems, plus a set of similar systems based on common modules, plus a set of unique systems, as shown in Figure 46. The CSP delivers either fully functional systems or a selection of modules to the launch vehicle development team. For example the common rocket motors are fully integrated and functional and are supplied from the CSP essentially ready for integration into the launch vehicle stack. In contrast, the common avionics suite is modular. The launch vehicle developers pick the appropriate modules for the design and integrate those into a particular system configuration for that launch vehicle. Finally, because the common systems and modules do not encompass all required functions of each launch vehicle, some portion of uniquely developed systems are required.

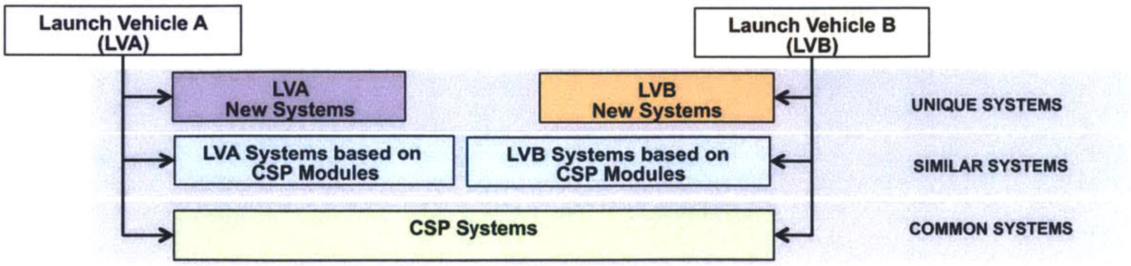


Figure 46: Each Launch Vehicle is comprised of unique, similar and common systems

CS2 initially attempted to use a simple distinction between "common systems" and "unique systems", however, as detailed engineering analysis showed system commonality was unworkable, module commonality was introduced as a third option. For example, the original vision for common avionics was to have a single avionics system common across all the launch vehicles. This proved too difficult to engineer, and the compromise position was the current configuration of a suite of compatible avionics modules. The flight termination systems also follow a modular approach. They are configured differently for each launch vehicle, but the wiring assemblies, ordinance and batteries are common.

The division of responsibility between the CSP and launch vehicle development teams is shown in Figure 47. The CSP is responsible for the procurement of the common systems and common modules. The launch vehicle development team is responsible for integration of the modules and the development of new hardware which does not have commonality with other vehicles.

From an organizational perspective, the CSP is structured as part of the supply chain arm of CS2's business. Some pieces of common hardware, like avionics, are manufactured in-house from supplied components. Other common systems are subcontracted to suppliers who make subassemblies by integrating components from lower-tier suppliers. Figure 47 depicts a stylized version of this supply chain. CS2 has approximately 35 companies involved in producing components or sub-systems for the CSP spread across 17 states.

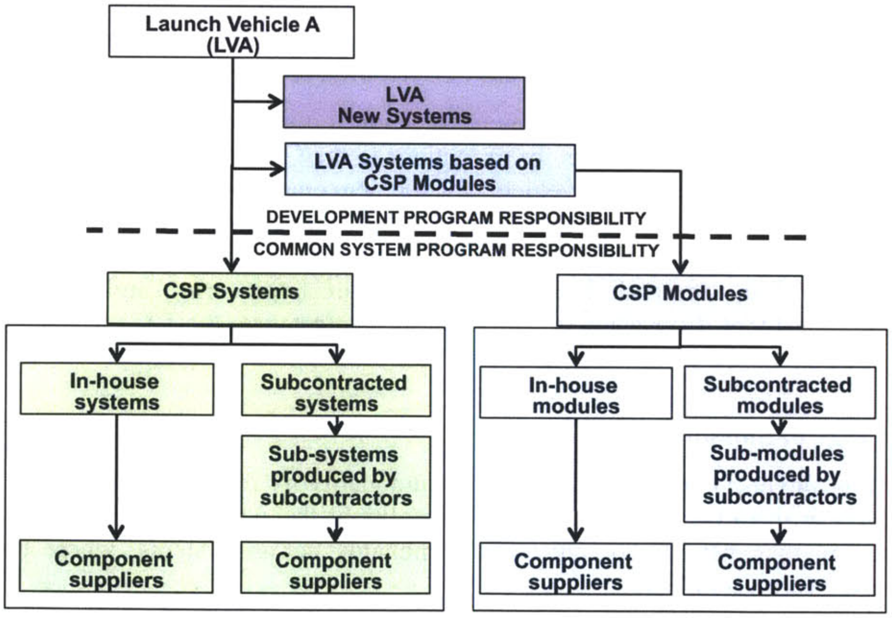


Figure 47: Supply chain responsibilities for each launch vehicle

Benefits Delivered by Commonality

Members of both the CSP and the launch vehicle programs had a clear and consistent idea of the benefits commonality achieved within CS2. The key benefits which the CSP achieved were, in approximate order of importance:

- Improved reliability;

- Lower cost; and
- Improved schedule performance.

The CSP attributed each of these benefits to specific causes. Improved reliability was achieved because common components were flown more often which made more test data available for common components and gave engineers a better understanding of how the hardware performed in flight. Lower cost was achieved primarily through economies of scale, because subcontractors could offer lower unit prices when given higher order quantities. CS2 found worthwhile savings even in small absolute increases in production quantity. For example, an increase from 1 or 2 per year to between 5 and 8 per year was found to give significant cost improvement. Lower cost was also achieved because the launch vehicle teams did not have to maintain a standing army of expert engineers for all of the common systems. Finally, the improved schedule performance was due to both the ability to maintain inventories of common parts and systems which had long lead times (in some cases over a year), and also a reduction in time spent on pre-sale contract negotiation because common suppliers are already on a standing (indefinite quantity) contract with CS2.

CSP Funding and Management

The CSP is funded by placing an adjustable mark-up on the variable recurring costs of common systems procured through the program. As an example with a 50% mark-up, if a particular launch vehicle development requires $1 million worth of flight termination hardware, that hardware will be ordered through the CSP and the price to the program will be $1.5 million. The development program is willing to pay the additional 50% because it avoids unique development costs in addition to sharing in the company-wide benefits of reliability, cost and schedule.

If common systems are notionally suitable for an LV being developed, then the program must use them. A formal review process manages requests for exceptions to the CSP. The review process consists first of negotiations between the launch vehicle development team and the CSP manager. If the issue is unresolved the resolution is escalated. The Vice-President of the development program argues the reasons for beneficial divergence before a board consisting of the Deputy General Manager, the Chief Engineer and the Vice-Presidents of Engineering and Mission Assurance. If the board agrees that divergence is beneficial in this instance, the LV program is permitted to design and build a new system.

CS2's Acquisition Strategy to Support Commonality

CS2 did not introduce any novel methods of increasing commonality by direct communication between its subcontractors, instead concentrating on commonality at the system level. CS2 did use a GFE-type strategy in one instance to improve commonality across systems, where the reliability and cost benefits were very clear.

CS2's approach is closest to a "Common Building Block" strategy which has been well planned and where divergence is well managed. In keeping with this approach, systems selected as common are discrete. Additionally, CS2 is closely involved in the design of the common systems. These two factors meant that CS2 could fully specify the common systems in subcontracts. This strategy concentrates all commonality coordination at the system integrator (CS2) level and therefore requires no coordination between subcontractors or contractual commonality incentives outside the CS2 organization.

CS2 did display one instance where it mandated commonality across its sub-contractors. CS2 supplied all contractors which needed to use ordinance (essentially explosives and detonators) as part of their sub-system assemblies with that ordinance. This approach is known as "Customer Furnished Equipment" ("CFE"), and parallels the federal acquisition method of Government Furnished Equipment ("GFE"). The reason for the bulk supply was because the ordinance was required to operate with very high reliability and so CS2 wanted control over the testing and verification of the ordinance prior to installation into the assemblies of the contractors. Testing was also more cost effective if done on a larger batch of ordinance, so CS2 could actually obtain cheaper prices for the sub-system assemblies at a given reliability level by supplying the ordinance itself. The strategy of supplying CFE fit well with CS2's original strategy of tightly specified common systems, because the CFE could be included simply as another aspect of the specification.

CS2 also noted some negative impacts of commonality on its acquisition strategy. Using commonality as a strategy increased the difficulty and expense of CS2 switching to use a different supplier for any of its common systems. There were reliability benefits in particular associated with CS2 remaining with the incumbent supplier. To minimize the risk of the suppliers increasing prices in response to CS2's dependence, CS2 attempted to negotiate 3 to 5 year supply contracts. The contracts were for indefinite quantities but contained quantity-price curves for each order period (often 1 year). The contracts also included year by year price escalation to make multi-year contracts more attractive. Additionally, CS2 attempted to maintain price competition by assessing prices of alternative suppliers and using these as leverage to encourage the incumbent to reduce costs, though in some areas of niche supply this was not always possible.

Variation in the product of a single contractor over time was also a threat to commonality. CS2 required detailed drawings and change reports from its suppliers and monitored these to ensure consistency over time from a single supplier's products. A lack of consistency would lead to a lack of commonality between launch vehicles built at different times, which would undermine the reliability benefits of commonality.

Viewpoints from CS2 on Acquisition Strategies for NASA

From time to time CS2 performs system integration or hardware development work for NASA. CS2 was therefore able to provide an industry perspective on how NASA could achieve more commonality across its exploration architectures. The interviews revealed a range of attitudes because the questions invited speculation and insight based on experience in the industry.

GFE

CS2 has worked extensively with GFE from both NASA and DOD, and therefore has views on how a commonality acquisition strategy based around increased amounts of GFE might operate. CS2 has been involved both as an integrator of GFE from the government and as a supplier of GFE to the government.

When supplying GFE, CS2 was more concerned with liability than with the loss of intellectual property. It was commercially comfortable with the intellectual property implications of GFE because it would normally be obvious if any systems or designs supplied as GFE were copied and legal action could be taken. CS2 also implied that government agencies could push for more extensive rights to the intellectual property in a contractor design in circumstances where that design was produced using government funding.

In terms of liability, however, CS2 was less sanguine. If a launch vehicle for which CS2 had supplied GFE failed, the anomaly review would be orchestrated by the launch vehicle prime contractor. That contractor would likely be a direct competitor of CS2. CS2 was concerned its influence on the review would be minimal, yet the review would have a conclusive impact on the apportionment of liability for the failure. Any appeal from the findings would be extremely expensive because of the complexity, detail and specialist nature of launch vehicle failure investigation. CS2 feared its supply of GFE made it vulnerable as a potential scapegoat for a competitor's failure investigation. CS2 did note that there were a range of GFE opportunities, and some represented a more "mission critical" role than others. The liability concern diminished as GFE systems become less mission critical.

Liability also played a role in CS2's view on receiving GFE. In one example, if GFE integrated into a CS2 launch vehicle failed, CS2 was not liable to its government customer for the launch failure. CS2 as system integrator also had access to all manufacturing and test records for the GFE system and could reject particular instances of the GFE based on those records. This additional oversight by CS2 did not affect its rights under the limitation of liability to its customer. It is unlikely CS2 would be comfortable launching the vehicle containing the GFE without both a waiver of liability and access to the engineering records of the GFE.

In addition to the legal concerns relating to GFE, CS2 stated two engineering heuristics relevant to GFE projects. First, the GFE should be fully designed, and preferably manufactured and delivered, before systems which interface with the GFE are designed. This avoids the situation where Company A builds to Company B's GFE specification, then the specification changes slightly in detailed design and Company A must rework aspects of its dependent design. Second, the GFE must capture all of the ancillary knowledge and equipment needed for the GFE to properly function. This knowledge includes design rationales and detailed operating instructions, as well as ground support and test equipment and procedures. CS2 gave one example where portions of GFE avionics were deactivated because the CS2 design teams were unsure what purpose those portions are intended to serve, and the government representatives who would have been able to explain the design had retired.

Contract Incentives

CS2 firmly believed that financial incentives could modify contractor behavior. CS2 pointed to underrun sharing in particular as a powerful incentive.

CS2 was also candid about the way firms assess incentives, suggesting that any incentive which operates based on a fixed metric will be analyzed for opportunities to maximize the metric score. This puts pressure on contract writers to develop incentives so that any contractor "optimization" of the incentive profits still produces a result aligned with customer expectations. The more specific the scoring criteria for the incentive fees, the greater the opportunity for contractors to strategize to maximize incentive profits.

Contract incentives are not the only pressure on performance at CS2, however. Market forces are an important concern in the launch vehicle market. Even without incentives for quality written into the contract, CS2's future orders are threatened if its launch vehicles fail.

Contracts Involving a Directed Subcontractor

CS2 cautioned against contractual arrangements where a prime contractor is directed to use a particular subcontractor. One executive went as far as to call this a "nightmare" scenario. The prime has no leverage over the subcontractor, and so the usual business practices which allow the prime contractor to control the costs and performance of the subcontractor do not work well. The government has some leverage over the subcontractor, but is often unwilling or technically unable to take on the day-to-day responsibilities of managing the subcontractor. There is a high switching cost in changing a directed subcontractor because it involves tripartite negotiations between government, prime and subcontractor, instead of an executive decision at the prime contractor level. The high switching cost reduces the incentives on the subcontractor for efficient, quality performance. The subcontractor is effectively in a monopoly with very high barriers to entry for other firms.

Leader / Follower Contracts

When given the opportunity to discuss possible solutions to multi-party commonality contracting, one executive at CS2 suggested a chain of reasoning which culminated in a suggestion for "leader-follower" contracts.

First, he reasoned, specialization of work by function is an efficient way of introducing some commonality into the system. Specialization simply means using the same teams or companies for the same functional areas across the exploration infrastructure. For example, Company C could develop ECLS Systems for the crew capsule, the lunar lander and the lunar surface systems. The major drawback is that after committing to using Company C, the incentive for Company C's ECLS System team to work efficiently diminishes, because of the high switching cost discussed above.

To introduce competition, he suggested "leader-follower" contracts, used during the Apollo Program and on the ICBM development projects. Often these contracts are used to set up a second source of production, but they can also be used to simply assure an alternate supply if the first source fails. A full description of this type of contract was provided in chapter 2.3. To briefly recap, if Company C is the system producer, Company D is contracted to closely track Company C's development efforts, understanding the design, its constraints and risks and attending meetings and design reviews. This lowers the switching cost for the government, possibly lowering the cost of acquisition of the system overall.

System oversight by the customer

A similar result to that gained from leader / follower competition could be achieved with diligent and sophisticated system engineering oversight from the customer. Effectively the customer would act as a check on Company C's production costs and timetables. Most interviewees at CS2 felt that to perform this engineering oversight well required active and ongoing engagement in development projects. Many government system engineers, now largely contract managers in their view, have not been given the chance to develop and / or continually practice these skills. A possible alternative is to appoint a single corporation which does have the requisite skills and experience as the system integrator. CS2 suggested that to preserve the integrity of the corporation as an overseer in this system the system integrator must not be permitted to allocate substantial non-integration work to itself.

Summary of key findings from CS2 Case Study

Question 1: How does CS2 as a system integrator encourage and manage commonality among its own subcontractors?

1. CS2 implements commonality at the system or module level, where it controls the design and the specifications. CS2 does not use direct communication between subcontractors to increase commonality.
2. CS2 adopted a GFE model to supply common ordinance across subcontractors because commonality of ordinance delivered obvious reliability and cost benefits.
3. CS2 believes the key benefits it obtains from commonality are, in order of importance, reliability, cost savings and schedule improvements.
4. Commonality is only applied to a subset of launch vehicle systems, but is applied across all launch vehicles.
5. On systems where commonality is applied, divergence is tightly managed and controlled, but there are mechanisms which allow beneficial divergence to occur.

Question 2: What does NASA need to consider in managing commonality across subcontractors like CS2?

1. A commonality acquisition strategy which uses GFE must address liability and intellectual property, and is less likely to succeed if designs are continually changing.
2. Directed subcontracts are difficult to manage and should be avoided.
3. Specialization of contractors coupled with a leader / follower contract arrangement may assist in developing commonality.
4. NASA requires strong systems engineering skills to effectively oversee a contractor which is in an effective monopoly position as a part of the commonality strategy.

4.3 CASE STUDY 3: COMMERCIAL LAUNCH VEHICLES

Introduction

The third case study examined another launch vehicle manufacturer ("CS3"). CS3 flies a range of payloads for customers including NASA.

The study aimed to answer two questions:

1. What strategies does CS3, as a launch vehicle integrator, use to encourage and manage commonality across its product family?
2. What are CS3's views on the commonality and acquisition strategies that are likely to work well for NASA?

The first question aims to assess industry practice in the same industry as CS2 to measure variation in commonality practice between organizations. The second question aims to gather further practical insight into feasible acquisition strategies from an organization with experience in space flight hardware.

CS3's Products and Business Strategy

CS3 produces a fleet of launch vehicles and sells launch services to a range of customers. There is significant commonality between variants in the fleet.

CS3 bases its business strategy around delivering high reliability launch vehicles. As a consequence, it is closely involved with all stages of manufacture and development.

CS3's Commonality Strategy

CS3's commonality strategy has four distinct approaches. These approaches work together to deliver higher levels of commonality than any one approach.

First, some commonality was designed into the launch vehicles during development. At first glance, variants bear close resemblance to each other. Common engines and core diameters are used across many variants in the fleet. Payload fairings are more diverse, but common fairings are still applied across several models. However, during the course of detailed interviews it became clear that the commonality was not as widespread as it superficially appears. In trying to take an initial point design and broaden the market appeal for that vehicle, commonality was sacrificed for performance. For instance, the tank skin thicknesses on otherwise common length tanks change to optimize performance. In one case, the margin for structural weight was *"a matter of ounces"*. The apparent platforming approach was in fact, in the words of one engineer, closer to *"taking a point solution, and walking it up"*. In the initial stages of family design, commonality benefits were generally lower priority than payload and delta-v performance.

The second approach to commonality was an attempt to create, in the future, more commonality between widely separated variants in the future. For example, there are currently two separate sets of avionics used among different vehicle families. Going forward, CS3 plans integration of those two separate sets into a single, common set of avionics. A similar process of convergence is planned for the vehicle upper stages.

The third approach to commonality is recapturing commonality. In part as a consequence of the push towards performance during initial development, divergence occurred. The systems and components which diverged now represent opportunities to increase commonality between variants in the future. For example, the different skin thicknesses could be made common in future. This is possible because new technology allows increases in actual performance over existing customer requirements, meaning some of the earlier trades towards uniqueness can be reversed while keeping performance constant. A 50% reduction in the number of assemblies used across the launch vehicle family is intended to be achieved after the retrospective commonality program. It is interesting to note that CS3 has largely chosen to invest the technology advances in commonality instead of increased performance.

The final approach to commonality at CS3 is ongoing process commonality in manufacture and operations between variants. Best practice lessons are shared between the manufacturing teams working on different launch vehicles, and similarly for operations. Processes are then made common if possible at the level of best practice across all CS3's variants.

Attention to commonality was widespread at CS3. Every interviewee was focused on and knowledgeable about commonality. The poster shown in Figure 48 was an early clue that CS3 practiced a commonality culture.[18] The interviews confirmed the widespread conscious and unconscious focus on commonality that characterizes a commonality culture. The emphasis of this culture was predominantly on reuse and the consolidation of existing designs across the entire product family. There were only a small number of instances where new systems were being planned to be used across all future variants. Therefore the commonality strategy at CS3 is best described as a commonality culture based around reactive reuse.

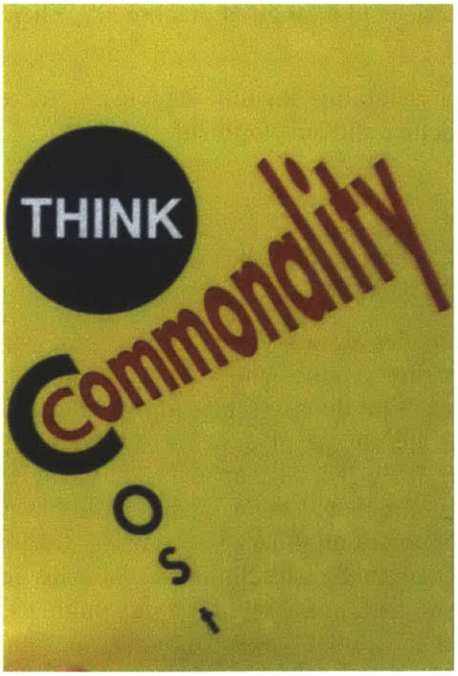


Figure 48: This poster promoting commonality at CS3 indicated a commonality culture

Benefits From Commonality Perceived By CS3

The commonality culture at CS3 is driven in part by the significant benefits perceived from commonality. The cost and reliability benefits seen in other case studies were present, and CS3 also identified "flexibility" as an important additional commonality benefit.

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[18] Additional detail on the poster which would have identified CS3 has been removed.

The cultural emphasis on reuse stems from CS3's perception that commonality increases reliability, and CS3's business model requires extremely high reliability in the launch vehicles. This makes new development very expensive because of the extensive testing involved in proving reliability. Even after testing, any new development presents a risk. In an industry where nothing is considered as reliable as flight-proven hardware, CS3 was very cautious about new development. Reliability was also increased by the process commonality mentioned above, where best practices in manufacture could be applied to more vehicles.

A second benefit to increasing commonality which was rated almost as highly as reliability was flexibility. Commonality between launch vehicles allows the reconfiguration of one vehicle to take another payload with a minimum of changes if the original payload is delayed. For example, building launch vehicle cores which have attachment points for boosters allows that core to be used for a higher payload or delta-v mission if necessary. There is a performance drawback to this commonality, because if the original mission launches as planned then the unnecessary structural mass of the attachment points decreases the performance. The flexibility also improves reliability. Interviewees cited cases of vehicles remaining in storage while their payloads were readied (known with a mixture of affection and frustration as a *"Hangar Queen"*). The storage time increases the risk that the vehicle will be damaged as work continues around it, and that reliability will suffer because pieces of the vehicle need to be changed out, repaired or upgraded because of time in storage. Each piece of repair or change involves rework to the vehicle and increases the likelihood of an undetected mistake.

Obviously this rework also contributes to cost, which is the third benefit of commonality often cited by interviewees. The usual cost savings of reduced design labor and economies of scale were mentioned. Several interviewees also argued that the reduction in configuration management, rather than reduced costs in manufacturing, was the dominant cost saving during the manufacturing phase. The cost reduction due to common manufacturing, for example in developing common skin thicknesses, was small because the high level of manufacturing automation meant the changes were simply a matter of loading a new computer design file. The real cost of the different variants occurred in the need to track quality assurance and testing procedures because the manufacturing process for the variants were slightly different. Keeping track of which variants had passed which tests and quality assurance processes was time consuming and difficult.

Drawback to Commonality

CS3 acknowledged that there were ongoing financial costs in identifying, evaluating and implementing commonality, but did not have estimates of the magnitude of those costs because in its commonality culture managing commonality was not drawn out as a separate item. The larger concern for CS3 was that moving to common systems decreased the reliability of their launch vehicle services viewed as a whole, while increasing the reliability of any one component due to the larger number of flights. Without commonality, CS3 have independently redundant components viewed from the perspective of the launch fleet as a whole. A failure of a component will only affect the subset of vehicles on which that component is used. The other vehicles can still be flown. With commonality, CS3 have the potential for a single common component failure to affect their entire fleet. This was a critical issue for CS3, and arguably the main brake on the rate at which commonality was increasing across families.

Commonality Funding and Management

Commonality funding and management are not centralized in CS3. There is no individual responsible for commonality across all product families. The closest instance was an individual in charge of the program to retrospectively implement commonality across a subset of variants.

The lack of centralized, coordinated responsibility appears to be largely a result of the commonality culture. The key individual in implementing commonality in each case was the person in charge of the functional area, for example avionics or propulsion. Commonality was so crucial to their oversight task that it was unnecessary to have a second person tasked solely with commonality responsibility.

Similarly, no separate funding streams were identified which specifically financed commonality improvements. It is hypothesized that this is because commonality and development funding were so closely linked under the CS3 culture.

The final management observation stems from a restructuring which brought variants closer across all phases of vehicle development and operations. This gave all levels of the organization better visibility across different variants. Several cross-variant commonality opportunities were investigated after the restructuring. Nothing had changed from a technical or mission perspective, but the way in which the organization was structured clearly affected the incentive for investigation of commonality opportunities.

CS3's Acquisition Strategy to Support Commonality

CS3's acquisition strategy supported commonality but did not identify any new methods for doing so. There were two key elements in the acquisition strategy. First, much of CS3's development and manufacturing was performed in house. CS3 was more involved than simply an integrator, which gave the company more scope to engineer commonality solutions across the entire launch vehicle. No interviewee particularly singled out improved commonality as a reason for performing engineering in-house, and it is likely that other reasons than commonality drove the in-house engineering.

Second, when dealing with suppliers, CS3 focused on building long-term relationships with its suppliers rather than encouraging constant competition. This allowed CS3 to have a single supplier consistently produce a particular common system without the price escalation commonly associated with commonality. One interviewee stated that it was made clear that CS3 and its suppliers *"sink or swim together"*, which keeps downward pressure on supplier prices. The alternative price control mechanism of competition was felt to be uneconomical in the low production quantities of CS3.

Over time, CS3 is attempting to increase the commonality of their suppliers. In so doing, an interviewee observed that *"if you start with common systems, common components are easy"*, but that without common systems common components were very difficult. For example, if two launch vehicle fairings are constructed from different materials or at different thicknesses it is very difficult to source common ordinance that will reliably cut both fairings. However, if the fairings are identical, sourcing common ordinance is easy.

Only in rare cases would CS3 procure material or components for its own suppliers ("Customer Furnished Equipment" or "CFE"). Two cases were given, one of ordinance and one of a unique alloy which had to be produced in mill-run quantities. The economic case for providing these direct was overpowering. In all other cases, the chief reason that CS3 was reluctant to supply CFE was to preserve the independent responsibility of the supplier. If CS3 supplied CFE, it left itself open to claims by the supplier that the cause of any poor or late performance by the supplier was that the CFE was late or inadequate. CS3 would prefer to be completely independent from the supplier, allowing it to compel performance from the supplier without excuse.

Viewpoints from CS3 on Acquisition Strategies for NASA

In addition to asking about the state of commonality at CS3, interviewees were asked about possible commonality acquisition strategies for NASA. The interviewees commented on GFE, directed subcontracts, common suppliers and leader-follower contracts.

GFE

CS3 was able to comment on Government Furnished Equipment both from its perspective of providing CFE to its suppliers *and* from its perspective as a possible recipient of GFE. The first observation interviewees made was that the concerns described above that CFE leads to "finger pointing" on liability and schedule also apply when GFE is supplied.

CS3 also related experience that showed it is critical GFE is introduced as early as possible. At one of the launch sites from which CS3 and other launch vehicle providers operate, a proposal to introduce a common, GFE flight termination system (FTS) onto all launch vehicles was mooted. The benefit was to give the launch site operator and the government more confidence in the proper functioning of the FTS of CS3 and other launch vehicle providers. However, supplying a piece of GFE which met the interface and environment specifications of *all* launch vehicles proved unworkable. In the view of CS3 it would have been possible to design a launch vehicle around the common FTS if the common FTS had been necessary at the outset. Because the GFE was suggested so late, retrofitting a common system into all vehicles was the only option, but it was shown to be a very expensive and difficult exercise and the effort was abandoned.

Directed subcontracts

CS3 considered directed subcontracts *"dicey"* as a strategy for commonality. Figure 49 shows a diagram of the directed subcontractor structure (right) compared with the conventional structure (left).

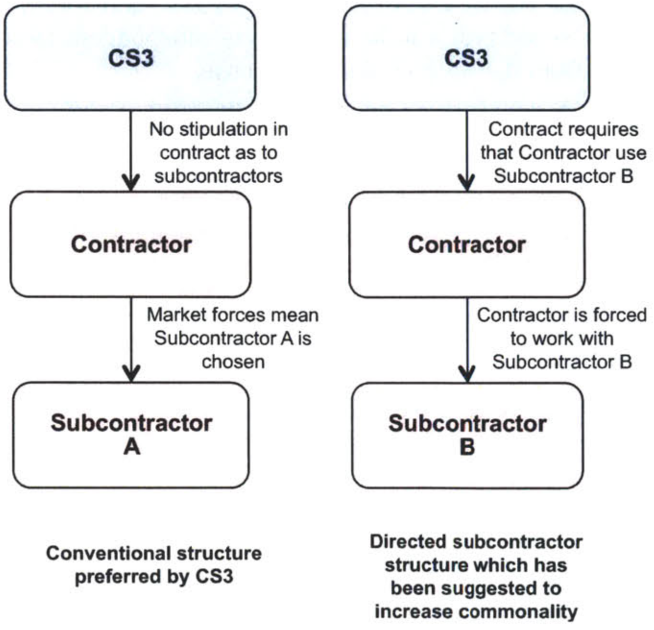

Figure 49: Directed subcontractor structure

The major reason for aversion to this arrangement was the disruption of the market forces which shape supply chains. Each contractor to CS3 had a relationship with its own subcontractors which was usually based on rational commercial grounds: quality, cost and attitude of the subcontractor. By forcing contractors to other subcontractors and *"creating a conversation that doesn't exist"*, there is a risk of upsetting a previously effective supply chain, according to the interviewee most responsible for supply chain management.

Direction by CS3 also risks CS3 being blamed by its contractor for poor performance lower in the supply chain. Under the directed subcontractor structure, CS3 instructs the contractor as part of its contract to use Subcontractor B. If the product from the contractor is defective or late, then the contractor may claim that Subcontractor B's poor performance is a result of CS3's selection of a poor subcontractor and not poor supervision by the contractor of Subcontractor B. It is also likely that such direction reduces the ability of the contractor to incentivize Subcontractor B to perform well. CS3 becomes responsible for managing the relationship between the subcontractor and the contractor.

Common suppliers

CS3 showed that having common suppliers does not guarantee commonality. As one example, prior to CS3 having a strong emphasis on commonality across all its vehicle lines, it had two separate contracts for helium pressurant tanks from a common supplier. Although the requirements were very similar, the delivered products were different. Each was optimized to the particular system despite the supplier having full visibility into the other design.

Leader-follower contracts

CS3 had limited experience with leader-follower contracts but offered two insights. First, the quantities of production in space systems were unlikely to be sufficient to allow full manufacturing competition. An interviewee offered as support the difficulty which Congress has had in approving the alternative engine development for the Joint Strike Fighter (although this is an example of full competition rather than a true leader-follower contract). The engines for the

Joint Strike Fighter were produced in quantities at least an order of magnitude larger than most space exploration systems.

Second, CS3 doubted whether sufficient incentive could be offered to a shadow follower to reward good performance by the leader. In an architecture constrained by affordability it will be difficult to justify large additional payments to the shadowing organization for no tangible output. On the other hand, if the payments are too small, it may be difficult to attract competent followers.

Summary of key findings from CS3 Case Study

Question 1: How does CS3 manage and co-ordinate commonality?

- CS3 focuses on four approaches to commonality:
    - commonality in initial vehicle designs;
    - recapturing commonality when technology improvements ease performance margins;
    - planning increased commonality by migrating uncommon systems to common systems for future variants; and
    - process commonality across manufacturing and operations without changing design aspects.
- CS3 manages its commonality strategies like an organization with a commonality culture, but focuses strongly on reuse of existing components and systems rather than the establishment of forward platforms.
- There is no single position of commonality responsibility, and each functional group within CS3 is itself responsible for commonality.
- CS3 sees reliability and cost benefits from commonality, as expected, but also sees the flexibility of switching launch vehicles for a given payload as a significant benefit.
- The weighting of the benefits of commonality against the reliability drawbacks of commonality is an important planning exercise for CS3

Question 2: What insights does CS3 have into commonality acquisition strategies for NASA?

- GFE can promote commonality but it must be identified early in the design phases of the project so other aspects of the design can interface with it. Legal liability and programmatic responsibility for the performance of the GFE must be allocated.
- It is unlikely that there will be sufficient production quantities to develop a leader-follower contract structure in an exploration architecture.
- Mandating particular sub-contractors may have cost implications because it disrupts established supply chains. It also requires allocation of legal liability and programmatic responsibility for the work of the directed sub-contractor.
- Using a common supplier does not guarantee commonality in the absence of customer-driven incentives for commonality.

CHAPTER 5: EVALUATION OF POTENTIAL ACQUISITION STRATEGIES

The previous chapters of this thesis have canvassed a wide range of commonality acquisition approaches, opinions and experiences. However these valuable resources need to be brought together into coherent strategies in order to be useful to NASA. The purpose of this chapter is to synthesize the learning on commonality acquisition presented in Chapters 2 to 4 into clear strategies, and to rationally evaluate the synthesized strategies for their impact on commonality. It is important to reiterate that acquisition strategies are not rigid, repeatable or scientific in the same way as engineering assessments can be. The results of this chapter should not be used to constrain the acquisition strategies used in the future. Rather they should be used to assess the general effect of aspects of the acquisition strategy on commonality. A NASA acquisition expert, armed with the insight into the industry players which comes from long acquisition experience and with more detailed information about the architectural elements of the successor program to Constellation, could use the evaluation framework in this chapter to assess the impact of acquisition strategies on commonality. Lacking both the long-term insight into the industry and the detailed architectural information, the recommendations in this chapter must be viewed as preliminary.

5.1 OUTLINE

The assessment method used in this chapter is split into three parts, shown in Figure 50. First, the Program Acquisition Structures and System Acquisition Structures developed in chapter 2.3 are examined. Then, each of the structures are evaluated to examine if they better meet the requirements of the NASA architecture and the requirements of best practice commonality. The third step is to take each high-level strategy and augment it with more specific contract improvements like financial incentives or particular intellectual property provisions. These specific contract improvements are designed to ameliorate weaknesses in the high level strategies.

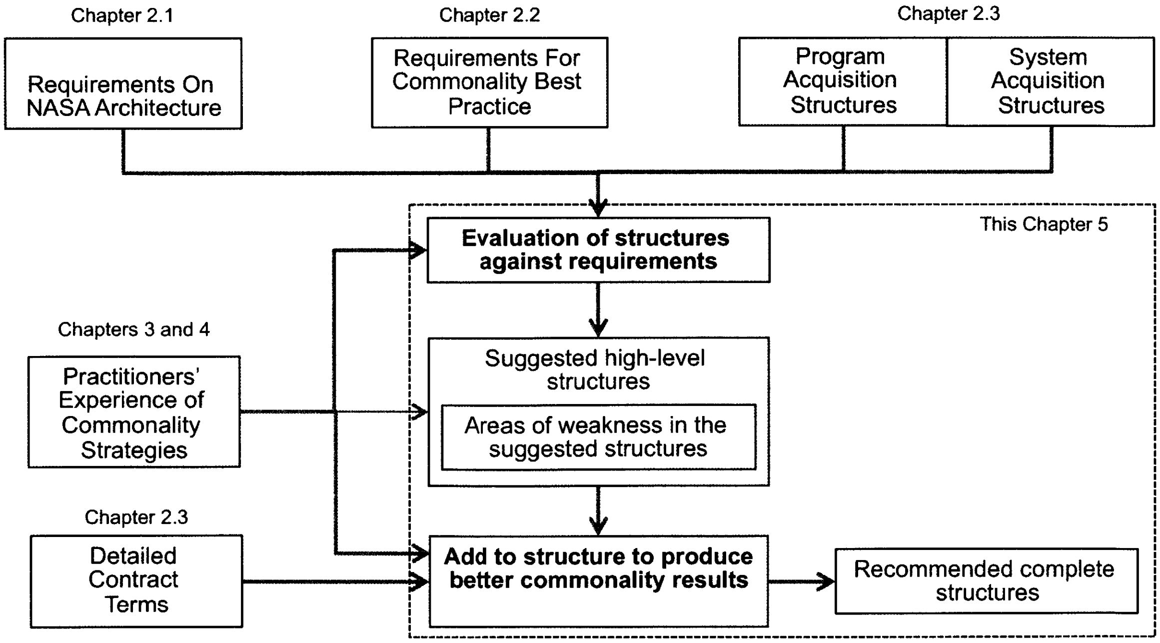

Figure 50: Commonality acquisition structure evaluation process

5.2 HIGH LEVEL COMMONALITY STRUCTURES

The evaluation process begins with the Program Acquisition Structures and the System Acquisition Structures discussed in Chapter 2.3 above. The possible architecture level structures for commonality are shown in Table 12, and the possible system level structures are shown in Table 13. For clarity, these will be referred to as "Acquisition Structures".

System-level Acquisition Structures affect contractor visibility and incentives on the same system over time. For example, fully competing the ECLS systems for a crew capsule, then an in-space habitat, then a planetary lander would produce different commonality between the ECLS systems than having a specialist contractor work on all ECLS systems. However, the different System-level Acquisition Structures would have only a minor effect on the commonality between different systems, say ECLS and propulsion.

Architecture-level Acquisition Structures affect contractor visibility and incentives over the entire architecture and over time. For example, having a sole prime contractor over each of a crew capsule, an in-space habitat and a planetary lander would produce different commonality than having a separate prime contractor for each with NASA defining system interfaces.

Table 12: Architecture Acquisition Structures

Architecture-level structure	**Description**	**For detailed discussion see**
Multiple primes, with NASA as system integrator	<u>Description:</u> NASA operates as the system integrator of elements produced by prime contractors. <u>Effect on commonality:</u> Low visibility of commonality between elements. Low incentive on any prime for commonality with others.	p.68
SETA	<u>Description:</u> NASA has extensive assistance on the system integration task from a commercial system integrator. <u>Effect on commonality:</u> Commercial system integrator can move between elements to increase commonality visibility.	p.69
Alliance contract between NASA and a single prime	<u>Description:</u> NASA and a prime contractor establish an alliance contract and work together as joint system integrators. <u>Effect on commonality:</u> Risk and reward sharing means that the prime contractor and NASA both benefit from beneficial commonality. This provides a natural incentive to proper evaluation of commonality.	p.70
TSPR	<u>Description:</u> NASA acts solely as a customer, and a commercial company handles all system integration. <u>Effect on commonality:</u> The prime has good visibility across all elements. Can be incentivized by NASA to implement commonality.	p.72

Table 13: System Acquisition Structures

System-level structure	Description	For detailed discussion see
Fully competitive	Description: Each time a system is developed, any qualified contractor may bid. Previous work will be taken into account, but is not determinative. Effect on commonality: Discourages commonality across projects, unless commonality is specified as a high-priority selection criteria.	p.75
Joint venture (JV)	Description: Two companies form a JV to produce multiple instances of a system they otherwise would have competed to produce. The JV is assumed to be one the companies willingly undertake. Effect on commonality: Gives visibility between systems and economic incentive for commonality if it is beneficial in the design / manufacture phase. Often difficult to find willing JV partners. May reduce competition, increasing prices.	p.77, p.119
Directed contractor	Description: A prime contractor is directed to use a particular subcontractor with previous experience in developing the system. Effect on commonality: Encourages obvious reactive reuse at component levels. Common subcontractor without more is insufficient to ensure common systems.	p.79, p.120, p.150, p.157
Long-term Supplier	Description: A particular contractor is mandated as the only contractor to be used for a particular system across the architecture. Effect on commonality: As for directed subcontractor. If requirements of future systems are well specified in advance, may encourage creation of common building blocks, rather than reactive reuse.	p.82
Build-to-Print	Description: Two contractors each undertake the development of the same system. The contractors are given the same specifications of form in the contract requirements to encourage commonality. Effect on commonality: Will encourage commonality if the systems are simple, but difficult to manage divergence.	p.83
GFE	Description: A contractor or NASA develops a system which will be supplied fully developed to other contractors as GFE to be integrated in their systems. Effect on commonality: System is likely to be common, but system engineering around the common system may be difficult and result in net detriment from using GFE.	p.85, p.121, p.149, p.156, p.157

System Acquisition Structures and Program Acquisition Structures have weak interaction. For example, a GFE System Acquisition Structure works better under a multiple-prime Program Acquisition Structure than under a TSPR structure, because the government is more closely involved in the former. However, the interaction is weak, and all System Acquisition Structures are feasible with all Program Acquisition Structures. NASA could develop a sound commonality acquisition strategy using any of the Program Acquisition Structures.

As has been shown in the previous chapters, the structural arrangement of NASA, prime contractor and subcontractor is not the only determinant of a successful commonality strategy. Significant improvements can be obtained by tailoring particular aspects such as contract pricing, intellectual property, management approach and task phasing.

Table 14 to Table 17 show the aspects of acquisition which can be implemented independently of the chosen system- or architecture- level strategy. Any of the acquisition aspects listed in the table can be added to affect the commonality outcome. Often, adding these aspects will incur greater costs to the acquisition as a whole, either in payments to the contractor or in NASA or integrator management expense. The options listed in these tables will be referred to as "Incremental Improvements".

The combination of Acquisition Structures plus Incremental Improvements will be referred to as an Acquisition Strategy.

Table 14: Incremental Improvements Relating to Contract Tasks and Structure

Contract tasks and structure		
Acquisition aspect	**Description and commonality effect**	**For detailed discussion see**
Single contract with design and manufacture phases	Description: A single contractor is awarded both the design and production phases of the contract. Effect on commonality: The contractor is incentivized to look at both the design and manufacture phases in evaluating commonality.	p.102
Separate contracts for design and manufacture	*Description:* One contractor undertakes design only. Then the contract is competed again for manufacture. The design contractor may win again. *Effect on commonality:* The split between design and manufacture means that the design contractor is unlikely to look at full-lifecycle commonality.	p.102
Leader / follower arrangement	Description: A contractor is awarded design and production work. A second contractor shadows the work of the first and can take over if the first performs poorly. Effect on commonality: Incentivizes thorough search for commonality by leader to avoid follower suggesting sensible commonality opportunities missed by the leader. Adjunct to specialization to keep competitive pressures on the specialist. If switching occurs on one product but not on others, may lead to divergence.	p.104, p.151, p.158
Contract for service	*Description:* NASA buys a service, not a development project. *Effect on commonality:* Incentivizes contractor to consider full lifecycle effects of commonality, assuming there is cost competition.	p.123
NASA obtains full IP rights	Description: Contractor is required to give all design and process information to NASA. Effect on commonality: Easier to reuse some or all of the existing design. NASA will have to pay contractor more however.	p.108
Contractor commonality exploration phases	Description: Contract phase specifically for exploration of commonality opportunities. Effect on commonality: Improves identification of commonality opportunities. Difficult to tell in advance if commonality will be useful.	p.104
Base assumption: Single contract with design and manufacture phases		

Table 15: Incremental Improvements Relating To Contract Pricing and Incentives

Contract pricing and incentives		
Acquisition aspect	**Description and commonality effect**	**For detailed discussion see**
Cost-plus-fixed-fee contracts	Description: Contractor is paid a fixed fee, plus its costs are reimbursed. Effect on commonality: Contractor has less disincentive to search for commonality because government pays labor costs of commonality search. However government also pays labor costs of new design so there is incentive to develop new design on government funds.	p.91
Fixed price contracts	Description: Overruns or underruns on the contract accrue to the contractor. Effect on commonality: Contractor more likely to look for and evaluate commonality benefits during lifecycle phases it is responsible for. More likely to discard commonality effects in later lifecycle phases.	p.91
Cost sharing	Description: Only a portion of the overruns or underruns on the contract accrue to the contractor. Effect on commonality: Gives a result between cost-plus and fixed-price contracts. Where the result lies depends on the amount of cost sharing.	p.92
Price redetermination	Description: The fixed price for the contract is adjusted after an initial period of experience by the contractor. Effect on commonality: Allows contractor to explore commonality ideas without impacting profit. Then incentivizes use of the common ideas under fixed price contracts.	p.97
Incentive awards for commonality	Description: Contractor earns extra profit for meeting commonality targets. Targets could be process related, fixed percentage commonality or based on lifecycle costs. Effect on commonality: Incentivizes reactive reuse and building block or forward commonality on systems within the visibility of the contractor. Incentives based on fixed levels of commonality may encourage absolute commonality rather than beneficial commonality.	p.94, p.122, p.150
Award fee strategies	Description: Contractor is evaluated by NASA at the conclusion of the project, and awarded a bonus payment based on how well the contractor met customer expectations (including commonality). Effect on commonality: Encourages contractor to consider what the customer wants from commonality and perform accordingly. Does not correct structural problems like lack of visibility.	p.95, p.143

Future projects buy-in	Description: Contractor or center develops a system, and receives “buy-in” later from other centers / contractors if the system is useful in their developments. Effect on commonality: Encourages design to consider future systems and reduce system cost. Does not improve visibility.	p.123
Base assumption: Cost plus fixed fee contract		

Table 16: Incremental Improvements Relating To Management and Systems Engineering

Management and Systems Engineering		
Acquisition aspect	**Description and commonality effect**	**For detailed discussion see**
Early contractor involvement with evolving requirements	Description: Design contract is given to contractor early, while requirements for other parts of the architecture are evolving. Effect on commonality: Difficult to plan for future systems because requirements are uncertain. Difficult to make performance-cost trades for existing systems because performance requirements change.	p.75
Fully defined up-front requirements	Description: Design contract is not given to contractor until architecture is fully defined. Effect on commonality: Systems can be planned for future requirements as well as current requirements. Performance-cost trades on current systems are more accurate.	p.121, p.128
Smart buyer strategies (expert NASA system engineers)	Description: NASA as customer is very familiar with the costs and performance limitations of the systems it is buying Effect on commonality: NASA can "sanity-check" performance-cost trades involving commonality. Gives NASA a better repository of existing projects in the minds of its engineers which it can recommend investigation of. Indirectly assists other commonality strategies like specialist contractors by reducing price risk associated with monopoly.	p.117
NASA / System Integrator insight on a continuous basis	Description: NASA (or its system integrator contractor) stations insight engineers with all contractors. Effect on commonality: Site-based insight engineers network with other site-based insight engineers to assess commonality opportunities. Increases visibility for widespread forward commonality.	p.107, p.151
Strong commonality team	Description: The NASA commonality team is well resourced and well led with strong high level management support and authority to force commonality. It is not responsible to any one project. Effect on commonality: The commonality team is able to force commonality evaluation, performance-cost trades and forcibly control divergence on individual projects in the interests of the architecture as a whole.	p.128
Fully funded projects	Description: Projects are fully-funded up-front and therefore have less need to show yearly progress in the form of flight tests etc to gain subsequent funding Effect on commonality: Assists in keeping requirements well defined and unchanging. Allows common articles to be produced first, and design based around those articles, rather than simultaneous development.	p.125
Base assumption: Early contractor involvement with evolving requirements		

Table 17: Incremental Improvements Relating To NASA-Wide Organizational Changes

NASA-wide organizational changes		
Acquisition aspect	**Description and commonality effect**	**For detailed discussion see**
Formalized re-use programs	Description: Centralized program at the center or NASA wide level handles inventories of components and systems, aggregating bulk buys and promoting reuse of spares. (eg JPL Flight Hardware Logistics Program) Effect on commonality: Lowers barriers to reactive reuse. Possible cost savings of several percent.	p.116
Centralized technology development	Description: Requests for new developments are sent to a single NASA or contractor point which can search for new commonality between variants. (eg Air Force Research Laboratories) Effect on commonality: New developments with commonality potential can be aggregated together. Most effective at the commonality level. May concentrate too much	p.118
Centralized, neutral organization as knowledge repository	Description: Information on existing developments are fed to a neutral organization which does not compete with contractors. Designs are cross-checked for commonality with existing designs of other contractors, allowing NASA to approach the existing designer for reuse. Effect on commonality: Improves visibility for reactive reuse. Does not incentivize commonality search or evaluation.	p.118
Base assumption: None of the above structures are included.		

Armed with these lists of Incremental Improvements and the preceding lists of Acquisition Structures, the best Acquisition Strategies can be identified. This analysis is conducted in the tables in Appendix B.

Each of the tables in Appendix B assesses one Program Acquisition Structure or System Acquisition Structure. First, the Acquisition Structures are assessed against the NASA acquisition requirements and the commonality best practice for each of reactive reuse, common building block and widespread forward commonality. Each Acquisition Structure is assessed assuming it uses only the base assumptions from the tables above. Then, where Incremental Improvements were considered to improve particular aspects of the commonality process, those improvements are noted in the table. Where Incremental Improvements were considered to improve the commonality process as a whole they are noted at the bottom of the evaluation column.

Entries marked in green (prefaced by (I) for black and white prints) perform a process satisfactorily. This means that the process can be undertaken and relevant heuristics are met. Entries in yellow (prefaced by (U)) show that it is uncertain whether the process can be performed satisfactorily, usually because there is a tension between a positive and a negative force for commonality, the magnitudes of which depend on the actual situation. Entries in red (prefaced by (W)) are unlikely to perform the process satisfactorily. Either there are significant barriers to undertaking the process or gathering inputs, or important heuristics are not met. A fourth category of entries are marked in grey, indicating that the Acquisition Structure has little effect on the execution of this process.

The final assessment for each Acquisition Structure is based on how difficult it is to set up and manage (Acquisition Affordability) and how much resistance establishing it is likely to meet (Political Risk and Regulatory Feasibility).

There is no distinction between Acquisition Structures which are very positive and those which are weakly positive, and similarly for negative processes. This is not a quantitative exercise, and disagreements over the proper categorization are to be expected. On the whole, however, the process separates good Acquisition Structures for commonality from poor ones. Detailed comparisons among the good or poor architectures are irrelevant, because fine distinctions will be swamped by other factors including the cost of managing the acquisition, the political appearance of the acquisition structure and the regulatory risks inherent in the structure.

Summaries of the results of the analyses are presented in Table 18 to Table 20. For each of reactive reuse, common building block and widespread forward commonality, the tables show whether the strategy is considered to be appropriate, borderline or ineffective, from the perspective of commonality. The Incremental Improvements which are considered necessary to deliver the strategy are marked inside each box.

More precisely, the color definitions also penalize structures which require extensive Incremental Improvements to make them workable, as shown below.

🟩 The Acquisition Structure plus the Incremental Improvements deliver a good structure. The Incremental Improvements required are not too extensive.
🟨 Either (1) the improvements listed turn this into a reasonable (but not good) structure; or (2) the improvements turn this into a good structure but the improvements are wide-ranging and difficult to implement
🟥 Regardless of the improvements, this structure is unlikely to be effective.

The usual NASA approaches to commonality of the relevant type on the Constellation program are boxed in dashed lines[19]. The same (I), (U) and (W) code is used to indicate the color on black and white prints.

In evaluating the preferred architecture, it is also important to consider the political and regulatory feasibility of each architecture. Table 21 presents a summary of the feasibility as determined by the tables in Appendix B. Each of the Acquisition Structures received a color code based on the "broad acquisition evaluation" criteria in Appendix B, then the lower score of the System-level and Architecture-level structure was used to indicate that architecture. For example, a Fully Competitive system level structure (Green) with a Sole Prime architecture level structure (Yellow) receives a Yellow overall score. The political and regulatory feasibility in Table 21 is

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[19] Note that the scoping interviews suggested widespread forward commonality was not attempted, so the reactive reuse structures are marked here, and show that expecting widespread commonality when using the same structures is unrealistic.

considered as an “overlay” to the summaries in Table 18 to Table 20. Strategies which are very well suited to commonality may not be particularly feasible from a regulatory point of view, and will therefore score well in Table 18 to Table 20 but poorly in Table 21.

Table 18: Strategy Assessments for Reactive Reuse

		Reactive Reuse Acquisition Strategies			
		Program Acquisition Structures			
		Multiple primes	**NASA With SETA Assistance**	**Corporate-NASA Alliance**	**Single TSPR Prime**
System Acquisition Structures	**Fully Competitive**	Firm requirements; architecture wide knowledge repository; strong commonality team; strong NASA IP negotiation (U)	Firm requirements; architecture wide knowledge repository; strong commonality team; strong NASA IP negotiation (U)	Firm requirements; architecture wide knowledge repository; strong commonality team; strong NASA IP negotiation (U)	Firm requirements; architecture wide knowledge repository; strong commonality team; strong NASA IP negotiation (U)
	Joint Venture	JV across wide range of systems; JV formed by market; fixed price contract; expert system engineering (U)	JV across wide range of systems; JV formed by market; fixed price contract (I)	JV across wide range of systems; JV formed by market; fixed price contract (I)	JV across wide range of systems; JV formed by market; fixed price contract (I)
	Directed Contractor	Fixed price contract; expert system engineering; strong commonality team (U)	Fixed price contract (I)	Fixed price contract (or other alliance incentives) (I)	Fixed price contract; good system engineering (I)
	Long-Term Supplier	Fixed price contract; expert system engineering; strong commonality team (U)	Fixed price contract (I)	Fixed price contract (or other alliance incentives) (I)	Fixed price contract; good system engineering (I)
	Build-to-Print	Firm requirements; architecture wide knowledge repository; strong commonality team; (U)	Firm requirements; strong commonality team; strong NASA IP negotiation (U)	Firm requirements; strong commonality team; strong NASA IP negotiation (U)	Firm requirements; strong commonality team; strong NASA IP negotiation (U)
	GFE	Not recommended due to partitioning between GFE team and development team (W)	Not recommended due to partitioning between GFE team and development team (W)	Not recommended due to partitioning between GFE team and development team (W)	Not recommended due to partitioning between GFE team and development team (W)

Table 19: Strategy Assessments for Common Building Block

		Common Building Block Acquisition Strategies			
		Program Acquisition Structures			
		Multiple primes	NASA With SETA Assistance	Corporate-NASA Alliance	Single TSPR Prime
System Acquisition Structures	Fully Competitive	Poor due to fragmentation of architectural tasks across systems and across time (W)	Poor due to fragmentation of architectural tasks across time (W)	Poor due to fragmentation of architectural tasks across time (W)	Poor due to fragmentation of architectural tasks across time(W)
	Joint Venture	JV at system level doesn't offer any advantages for developing a common building block to be used across architecture (W)	JV at system level doesn't offer any advantages for developing a common building block to be used across architecture (W)	JV at system level doesn't offer any advantages for developing a common building block to be used across architecture (W)	JV at system level doesn't offer any advantages for developing a common building block to be used across architecture (W)
	Directed Contractor	Poor due to fragmentation of architectural tasks and difficulty incentivizing contractor to develop for future (W)	Difficulty incentivizing contractor to develop for future (common contractor does not lead to common systems over time) (W)	Difficulty incentivizing contractor to develop for future (common contractor does not lead to common systems over time) (W)	Difficulty incentivizing contractor to develop for future (common contractor does not lead to common systems over time) (W)
	Long-Term Supplier	Cost sharing for future building block instances (or other incentive to commonality); expert systems engineering; strong commonality team (U)	Firm requirements; lifecycle cost incentives; strong commonality team (U)	Firm requirements; lifecycle cost incentives; strong commonality team (U)	Firm requirements; lifecycle cost incentives; strong commonality team (U)
	Build-to-Print	Workable with strong commonality team on aspects of architecture with firm, unchanging requirements (U)	Workable with strong commonality team on aspects of architecture with firm, unchanging requirements (U)	Workable with strong commonality team on aspects of architecture with firm, unchanging requirements (U)	Workable with strong commonality team on aspects of architecture with firm, unchanging requirements (U)
	GFE	Firm requirements; good system engineering; lifecycle cost incentives; strong commonality team; liabilty / responsibility arrangements; protection of IP (I)	Firm requirements; lifecycle cost incentives; strong commonality team; strong authority for expert system integrator (I)	Firm requirements; strong commonality team; (I)	Firm requirements; lifecycle cost incentives; strong commonality team (I)

Table 20: Strategy Assessments for Widespread Forward Commonality

		Widespread Forward Commonality Acquisition Strategies			
		Program Acquisition Structures			
		Multiple primes	**NASA With SETA Assistance**	**Corporate-NASA Alliance**	**Single TSPR Prime**
System Acquisition Structures	**Fully Competitive**	Poor due to fragmentation of system responsibilities, therefore lack of incentive to consider other systems or future development (W)	Poor due to fragmentation of system responsibilities, therefore lack of incentive to consider other systems or future development (W)	Poor due to fragmentation of system responsibilities, therefore lack of incentive to consider other systems or future development (W)	Poor due to fragmentation of system responsibilities, therefore lack of incentive to consider other systems or future development (W)
	Joint Venture	JV will be limited to system-level commonality, therefore unsuited to widespread commonality (W)	JV will be limited to system-level commonality, therefore unsuited to widespread commonality (W)	JV will be limited to system-level commonality, therefore unsuited to widespread commonality (W)	JV will be limited to system-level commonality, therefore unsuited to widespread commonality (W)
	Directed Contractor	Directed subcontractors are not a good strategy for widespread forward commonality because there is no forward looking incentive in subcontractor selection (W)	Directed subcontractors are not a good strategy for widespread forward commonality because there is no forward looking incentive in subcontractor selection (W)	Directed subcontractors are not a good strategy for widespread forward commonality because there is no forward looking incentive in subcontractor selection (W)	Directed subcontractors are not a good strategy for widespread forward commonality because there is no forward looking incentive in subcontractor selection (W)
	Long-Term Supplier	Coordinated incentives across the primes. Leader / Follower arrangements to keep costs low. Good system engineering; Firm requirements (I)	Full lifecycle cost incentive on system integrator and specialized subcontractor. Leader / follower arrangements. Firm requirements (I)	Full lifecycle cost incentive on system integrator and specialized subcontractor. Leader / follower arrangements. Firm requirements (I)	Full lifecycle cost incentive on prime. Leader / follower arrangements. Firm requirements (I)
	Build-to-Print	Structure is not flexible / responsive and is too difficult to set up and manage each time a new commonality opportunity appears (W)	Structure is not flexible / responsive and is too difficult to set up and manage each time a new commonality opportunity appears (W)	Structure is not flexible / responsive and is too difficult to set up and manage each time a new commonality opportunity appears (W)	Structure is not flexible / responsive and is too difficult to set up and manage each time a new commonality opportunity appears (W)
	GFE	GFE is not a good strategy for continuously identifying / evaluating and managing divergence. (W)	GFE is not a good strategy for continuously identifying / evaluating and managing divergence.(W)	GFE is not a good strategy for continuously identifying / evaluating and managing divergence.(W)	GFE is not a good strategy for continuously identifying / evaluating and managing divergence.(W)

Table 21: Summary of Political and Acquisition Policy Feasibility and Likelihood

	Structure political and acquisition policy feasibility and likelihood			
	Multiple primes	**NASA With SETA Assistance**	**Corporate-NASA Alliance**	**Single TSPR Prime**
Fully Competitive	(I)	(I)	(W)	Difficult across expl. arch. (U)
Joint Venture	Assuming the JV exists (U)	Assuming the JV exists (U)	Assuming the JV exists (W)	Assuming the JV exists (U)
Directed Contractor	Is occasionally used (U)	(U)	(W)	Difficult across expl. arch. (U)
Long-Term Supplier	(W)	(W)	(W)	(W)
Build-to-Print	(I)	(I)	(W)	Difficult across expl. arch. (U)
GFE	Is occasionally used (U)	(U)	(W)	Difficult across expl. arch. (U)

5.3 SELECTION AND DISCUSSION OF PREFERRED ACQUISITION STRATEGIES

The preferred Acquisition Strategies are shown in green in Table 18 to Table 20. This section describes why those strategies were selected.

Results are independent of Program Acquisition Structure

The first point to note is that the results are broadly independent of the Program Acquisition Structure. The reason is that the Program Acquisition Structure has two effects on commonality, and the analysis at this level of detail was unable to distinguish the Program Acquisition Structures on these effects.

The first effect is system engineering. A strong system engineering team improves the ability of systems to make cost-performance trades, useful in all three of the identify / implement / evaluate commonality stages, and provides lifecycle information which is valuable in the "evaluate" stage of the commonality process. It is not possible to say whether a NASA system engineering team leading multiple primes, the services of a dedicated SETA, a single TSPR contractor or a new fusion of these in an Alliance contract would be most effective at performing system engineering.

The second effect is cross-contractor willingness to share information and intellectual property. On the one hand it is possible to argue that sharing is more easily incentivized in the TSPR and Alliance structures where, theoretically "everyone is on the same team". On the other, the skeptical attitude to sharing shown through the contractor interviews and in Scherer's qualitative analysis suggests that the transfer of valuable intellectual property between contractors would still be limited within a TSPR-led consortium or an Alliance.

Therefore this analysis proceeds on the basis that the preferred commonality acquisition strategies are independent of the Program Acquisition Structures chosen. If more detailed analysis or deeper experience show that the Program Acquisition Structures affect systems engineering or willingness to share intellectual property then those structures which score better on those fronts will be better acquisition structures for implementing commonality.

Reactive reuse

For reactive reuse there are three good system-level strategies shown in Table 18. The best strategies, in approximate order of preference, are a directed contractor, a joint venture or a long term supplier at the system level. The directed contractor and joint venture score moderately well on the assessment summarized in Table 21, reflecting their moderate reduction in competition, while the long-term supplier scores poorly reflecting the truly anti-competitive nature of such a structure.

Under a directed contractor structure, which occurs when a contractor with experience building a previous system with significant anticipated commonality is chosen to build the new system, the contractor has the visibility to undertake the reuse because its institutional memory extends to the previous system. This gives the contractor a very good understanding of the systems, how they work and how easily they can be reused on other applications. The contractor is likely to own the intellectual property to its own designs, and take responsibility for them, removing two of the usual barriers to reuse.

However, as the case studies and scoping interviews showed, simply having the same contractor build two systems is insufficient for commonality. The reuse options can be improved by placing the directed contractor on a fixed price contract. The fixed price contract incentivizes low up-front costs and low testing and commissioning costs, and the contractor is likely to explore reuse opportunities to achieve these cost savings without compromising reliability. The incentive structure could be extended one step further by including an award fee tied to a life-cycle cost model. This would encourage reuse from designs actually in use to increase operational-phase commonality and reap the associated life-cycle cost benefits. It would not matter if the lifecycle cost model contains estimates and uncertainties, so long as it incentivizes trades being made in the general directions that lower lifecycle costs in comparison with development costs.

One drawback with the idea of a directed contractor is the possibility that the contractor exploits NASA's dependence on its experience and negotiates a higher fixed price. To some extent such price rises should be expected, and as long as the rise does not exceed the net commonality benefit, NASA still benefits from the directed contractor strategy. NASA maintains some price leverage because it can switch to an alternative contractor (although it loses the commonality benefit) if prices become too high. Additionally, as an insurance policy against this strategy, NASA could negotiate a NASA-wide license to the intellectual property rights for use by NASA on the exploration architecture. This would give NASA the option of continuing to build common systems itself. Taking that idea one step further, NASA could require the right to license another commercial company to use that intellectual property. This would preserve the option for NASA of moving to a second source for manufacture, which would be particularly important for systems which NASA does not have the capability to manufacture in-house.

Joint ventures are a second option for encouraging reactive reuse. A joint venture occurs when two organizations which would otherwise have independently bid for and developed unique systems instead bid as a single entity to develop both systems together. The discussions with practitioners showed that joint ventures are only good strategies if they exist naturally, and such a natural existence cannot be widely assumed. However, acquisition personnel should be aware of possible opportunities to encourage the formation of joint ventures to supply systems with commonality potential. The joint venture is likely to increase the visibility between the different contractors within the joint venture, which will improve the identification of commonality opportunities.

The third feasible strategy for reactive reuse is a long-term supplier. The supplier is likely to reuse aspects of previous designs to reduce cost and risk. In terms of reactive reuse, the advantages are the same as for the directed contractor discussed above. The distinction between the two in commonality advantages only becomes clear in the building block and widespread forward commonality strategies.

However, the disadvantages of the long-term supplier are more pronounced than for the directed subcontractor. Establishing a long-term supplier is a sole-sourcing approach which operates over a longer timeframe than the directed subcontractor. This makes it more challenging to justify under the current Federal Acquisition Regulations. The long-term supplier also has more power because NASA becomes more dependent on continuity of supply from the long-term supplier. If leader-follower contracts are needed to introduce competition into what would otherwise be an effective monopoly, the costs of the follower contracts may significantly reduce the net benefit from the overall commonality strategy. A combination of fixed price contracts and award fees based on lifecycle cost, similar to that used for a directed subcontractor, will be effective in incentivizing the implementation of feasible reuse opportunities.

A fully competitive structure offers minor benefits to reactive reuse. The high level of competition incentivizes up-front cost savings and reuse of heritage parts or systems is one way to achieve this. However, the fully competitive structure does not give companies insight into or intellectual property rights in any designs which were not built by them in the past. This is likely to lead to significant overestimates of commonality initially, which are later pared back to better reflect reality.

Build-to-print, where the government designs the system in advance, is likely to be only moderately successful in encouraging reactive reuse. The key drawbacks to build-to-print are that the government may only have a superficial understanding of the systems previously built for it, or may not have the intellectual property to the designs even if it has the understanding. Additionally, build-to-print is a strategy which places significant up-front work on the government.

For reactive reuse, GFE is considered an infeasible strategy because it offers only a *mechanism* for re-use of existing government equipment once the opportunity has been identified, rather than being a strategy which could provide *incentives* to search out and evaluate a range of reuse options. GFE is a more appropriate choice for implementing building block commonality.

Therefore, considering Table 18 and overlaying Table 21, the best strategies for reactive reuse are likely to be a directed subcontractor at the system level, with a program level structure comprising multiple-primes or NASA with a SETA contractor. Joint ventures occur too rarely to be a widespread strategy, and long-term suppliers pose too many regulatory obstacles.

Building block commonality

For building block commonality, the right strategy is less clear than for reactive reuse. Table 19 shows that the choice is between a straightforward but inflexible build-to-print structure, a more complex but more versatile GFE structure, and a long-term supplier which presents competition difficulties. On balance, each of these strategies has its place in a common building block strategy, as shown in Figure 51.

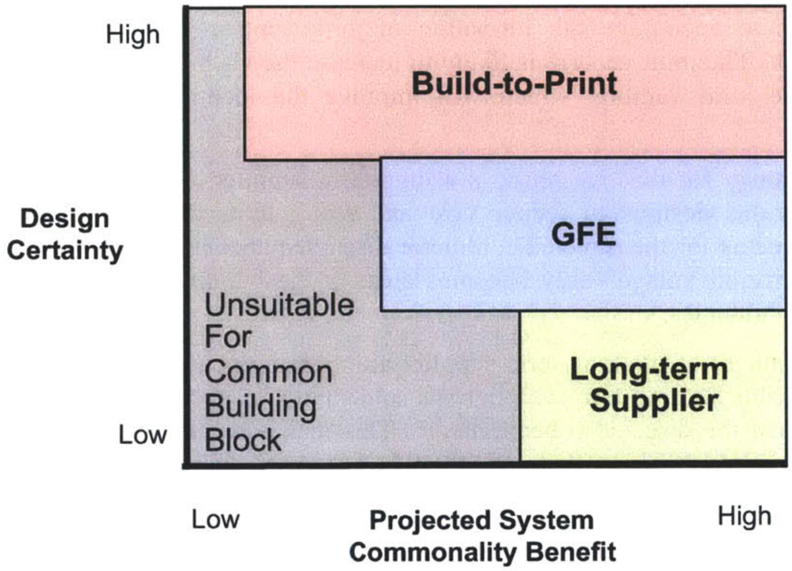

Figure 51: Suggested System Acquisition Structures for Common Building Block

For designs where the common design is clear-cut and divergence is therefore unlikely, a Build-to-Print strategy is a good strategy. A build-to-print strategy, which occurs when the government specifies a design which contractors then manufacture, uses multiple system-level contractors for the system manufacture and is attractive from the point of view of competition as shown in Table 21. It is also easy to understand, manage and implement. Contractors are comfortable with the risks presented by the government defining a design, in particular because it is clear where the liability and programmatic responsibility for the design lies. The key disadvantage to the build-to-print strategy is that the design must be performed early, and coordination of design changes in the face of divergence is difficult. These disadvantages become more pronounced as the initial certainty over the common design decreases.

For a moderate level of uncertainty in the design, a GFE strategy is preferred. Although the GFE should still be contracted and produced early relative to the systems it will be integrated with, it has a single organization in charge of the common system until integration. This increases the barrier to individual projects optimizing the building block for performance in their projects at the expense of program-level benefits to commonality. The GFE contractor acts as a central and independent repository for change requests which allows divergence to be managed in a more considered fashion.

On the other hand, a GFE strategy is not a preferred approach under the current NASA acquisition policies. It requires significant NASA management time to co-ordinate the GFE contractor and the individual projects. There is risk that the GFE may not integrate properly with the individual projects, requiring rework. The need to produce GFE before other interconnected systems could stretch schedules, which is also unattractive from NASA's point of view. From a contractor perspective, GFE is also unattractive because it intertwines liability for systems between the government as intermediary, the GFE supplier as the developer and the system integrator. In particular, GFE suppliers are unwilling to supply flight critical systems when their influence on failure investigation panels is limited, and integrators are unwilling to give their competitors which supplied GFE weight on panels because of the sensitive nature of those investigations.

A final alternative is to use a long-term supplier. The advantage of the long-term supplier for common building blocks is that the supplier knows they have a long-term contract and so the supplier can be incentivized to invest in commonality early in the program, developing sensible, sustainable common building blocks for future years. The long term supplier can develop common building blocks where divergence is constantly managed over time, in contrast with GFE where the specifications of the GFE to be provided are rigid and difficult to change on an ongoing basis. The flexibility the long-term supplier offers is particularly useful when the initial knowledge about the design is low. The disadvantages of the long-term supplier in terms of its monopoly position which were discussed above under reactive reuse are still present. The cost of managing the long-term supplier, either by introducing a follower or by accepting the price rises that stem from the monopoly, make this strategy a useful one only when there are high anticipated benefits from the commonality.

All of the structures, but particularly Build-to-Print and GFE are helped by a strong commonality team. The role of this team is to manage divergence, forcing systems integrating the GFE to resist modifications unless justified by benefit across the architecture. The commonality team must have the authority to impose these architecture-level decisions. Divergence management is particularly important given that there will be long offsets between the initial development of the common building block and the development of the final systems to use the common building block.

Strong system engineering is also important to ensure that the building block is being designed for the right requirements, and that the interfaces for the building block remain consistent over the offsets of several years. This is one of the reasons why a strong program level system engineering is so important.

Finally, in the case of the GFE contractor and Long-Term Supplier, incentives are needed to manage divergence and produce a system that is appropriate for future applications. The best way to do this is to use a cost-plus contract with incentives based on lifecycle cost. The lower the estimated lifecycle cost of the system to NASA, the better the GFE contractor should be rewarded. A fixed-cost contract is likely to discourage the contractor from fully exploring opportunities for future commonality. The contract administrators on the cost-plus contract must understand that the contractor must be allowed to make commonality investments in the development of the initial building blocks, and should be prepared to see the contractor present a different cost profile to unique development. More radically, NASA could pay an award fee based on commonality at regular intervals during the contract. For example, the contractor could have the opportunity to earn an additional 5% per year based on NASA's assessment of its attention to commonality. In both of these strategies, strong system engineering is needed to correlate good (not merely adequate) performance with contract rewards. NASA should not be in a position where the contractor is explaining to it why it deserves the award fee; the instruction should flow the other way.

If a SETA contractor is used at the program level, part of its responsibility should be to backstop NASA's assessment of award fees, and to maintain independent lifecycle cost estimates for the common building block and the systems which use it. For these reasons the SETA contractor must be independent from the GFE contractor or Long-Term Supplier, and should not be involved in any design and construction at all.

Table 21, in summarizing the political and policy feasibility of the systems, shows that the order of preference between system-level strategies is Build-to-Print, then GFE, then a Long-Term Supplier. At the Program-level, a multiple-prime structure or a NASA-with-SETA structure are preferred.

Therefore, the recommended strategies for developing common building blocks are, in order of preference, Build-to-Print, GFE and a Long-Term Supplier. If it is difficult for the government to fully specify the initial design at the outset, GFE may be preferable to Build-to-Print.

Widespread forward commonality

Table 20 shows that only a Long-Term Supplier is feasible for widespread forward commonality. No other structure gives the forward-looking incentives to invest widely in commonality. However, Table 21 shows that a Long-Term Supplier is infeasible under the current political and acquisition policy environment. This leads to the conclusion that NASA should not attempt widespread forward commonality as a general strategy, although it may be justifiable in very limited areas, for example where market conditions mean that there is only one effective supplier in any case.

If NASA were to attempt this structure, it would need to retain very close control and supervision over the structure to minimize allegations of anti-competitive behavior by the specialist contractors. The Long-Term Suppliers must be incentivized to minimize lifecycle costs across the whole portfolio of systems they develop. Award fees should be based on lifecycle costs and include the lifecycle implications of commonality with previous systems. At an extreme, contracts for service could be used where the contractor is responsible for the lifecycle costs itself. Program management must independently track the lifecycle costs.

The contractors must also be incentivized not to abuse their monopoly positions by increasing prices. Leader-follower contracts are one way to maintain downward pressure on the costs of acquiring the systems, if the commonality benefit is expected to outweigh payments made to the follower.

Finally, strong system engineering is required to keep requirements as firm as possible, allowing the Long-Term Supplier to forecast needs and develop systems which invest in forward requirements.

5.4 BLENDING THE COMMONALITY STRATEGIES INTO AN INTEGRATED WHOLE

For systems where extensive work has already been done on similar systems, requirements change slowly and up-front costs are most important, reactive reuse is dominant and a directed subcontractor approach should be used.

For systems where new development is needed, but there are common functions and environments across different applications, a common building block approach is likely to be best and a Build-to-Print strategy or GFE providers should be selected.

No acquisition strategy was found which was feasible for widespread forward commonality, and it is not recommended that NASA attempt such an approach.

5.5 COMMENT ON CURRENT NASA STRATEGIES

The current NASA strategies were shown in dashed outline in Table 18 to Table 20. On average, the strategies are reasonable (yellow) for reactive reuse and some common building block strategies, but poor (red) for the widespread forward commonality. In part, this explains why NASA has had more success with reactive reuse and common building block strategies. However, it may also indicate that NASA's acquisitions are not well suited to widespread forward commonality, so there has been little pressure on NASA to evolve acquisition structures that promote widespread forward commonality.

In light of the research conducted for this thesis, it is likely to be both. There is little doubt that NASA can obtain most of its theoretical potential commonality benefit through reactive reuse and common building block strategies. The comments from the Constellation commonality team and the launch vehicle case studies supported this.

Given this, it is not essential to remold NASA strategies to accommodate widespread forward commonality approaches. However, more can be done to support system acquisitions where reactive reuse or common building block strategies are expected.

CHAPTER 6: RECOMMENDATIONS, FINDINGS AND CONCLUSION

This chapter concludes this thesis by summarizing the recommended acquisition strategies for commonality within NASA, and listing the key findings of the thesis research before recommending the next steps in finessing the detail of the best acquisition strategies. The further work is probably best conducted from within NASA, given the detailed information on architectures that is required.

6.1 RECOMMENDATIONS FOR A COMMONALITY-FOCUSED ACQUISITION STRATEGY

If NASA is serious about pursuing commonality as a major component of its exploration strategy, current acquisition practice is at odds with architectural direction. The approach that sees NASA as system integrator across multiple prime contractors, with each system competitively awarded as it becomes needed, imposes significant obstacles to commonality best practice.

However, commonality is not a goal in itself. The acquisition strategies recommended for commonality may cost more than the benefits of commonality. The strategies are designed to encourage developers to only pursue commonality where it is cost effective, but the *implementation of the strategies themselves* may be costly. The current NASA strategy based on competition has been somewhat effective in developing complex spaceflight systems over the past fifty years, and commonality based acquisition may well do worse.

An acquisition strategy for NASA in 2011 should give thought to the following recommendations which, taken together, would support commonality better than traditional approaches.

1. NASA should focus on reactive reuse and common building block strategies for commonality. The NASA acquisition task is too broad to suit widespread forward commonality.

2. To implement reactive reuse, NASA should first identify any systems which are likely to have significant commonality with existing systems. Then NASA should assess whether it is possible to have a directed contractor develop that system.

3. To implement common building block commonality, NASA should focus on identifying a small number of high-value candidate systems for common building block commonality, and performing evaluation of commonality potential. For the potentially common systems, NASA should establish one of two acquisition strategies:
    a. For systems which NASA can design now and which will not change across the different projects in the exploration architecture NASA should begin a "Build-to-Print" acquisition strategy, complemented by lifecycle incentive payments and commonality award fees.
    b. For systems which NASA can identify as potentially common, but where a separate contractor possesses the experience to design these systems or where there is likely to be design changes through development, NASA should develop acquisition structures to supply these systems as GFE. Again, lifecycle incentive payments and commonality award fees will improve investment in forward commonality.

4. The program-level contract and management structure must be built around a strong system engineering team which has the vision and authority to force projects and systems into performance-cost compromises that best represent value for the program.

5. NASA must build a strong commonality management team which has the authority and experience to compel projects to take actions in the interests of the architecture as a whole, even to the detriment of the project. That team should be involved from the outset of the project, and their authority written into all architecture contracts.

6.3 FURTHER WORK

There is scope for further work to be conducted to build on this thesis. However, most of the work is at a level of specificity most suitable for internal investigation at NASA, or by researchers with complete access to NASA architecture plans. The three areas of future work are:

1. The acquisition strategies developed in this thesis work best if it is known in advance whether reactive reuse, building block commonality or widespread forward commonality will be most effective. Given the likely architectures NASA will adopt, which commonality strategy should NASA shape its acquisition strategy towards? This analysis should be based in part on the quantities and frequencies of production needed from the essential exploration elements.
2. The acquisition strategies most suitable for commonality must be balanced against acquisition strategies which have other benefits such as simplicity, affordability or flexibility. What are the expected benefits of commonality across NASA's exploration architecture, and how do these compare to the expected benefits from adopting acquisition strategies less suitable for commonality?
3. GFE is proposed as a solution for building block commonality. There are a number of NASA projects which have used GFE in the past, particularly on Constellation. These projects would be a good source of detail and refinement on the GFE strategy.

6.4 CONCLUSION

There is no doubt there is potential for extensive use of commonality in space exploration architectures, and strong potential benefit to be gained. Implementing that commonality, however, requires support throughout development, and that support begins with an appropriate acquisition strategy. No acquisition strategy is perfect for commonality, and of those that work well some are at odds with the Federal Acquisition Regulations or NASA Procurement Policy. There are, however, some strategies which work better than the traditional model of full competition on all systems. The most promising strategies are to encourage reuse by preserving the same system-level contractors over time, and to establish common building blocks by developing them as build-to-print designs, GFE projects or through long-term suppliers.

Commonality is not a panacea for all exploration architecture ills. It requires careful forethought and ongoing dedication to implementation. Commonality's reputation has suffered in the past from overstated benefits and unforeseen drawbacks. In truth, its benefits are unlikely to be spectacular, yet they are achievable and realistic and should not be discarded lightly. The cost conscious space exploration of the twenty-first century cannot afford to ignore them. Appropriate acquisition strategies lay the first stones along the path to space system commonality.

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APPENDIX A: LIST OF SPECIFIC SCOPING INTERVIEWEES

Role / Title	**Organization**	**Project Expertise**
Professor, Space Systems Acquisition	Defense Acquisition University	Defense Aerospace Systems
Electra Project Lead	JPL	ELECTRA (Common Software Defined Radio for Mars)
Engineer, Office of Chief Engineer	JPL	JPL Avionics Hardware
Research Associate	Lean Aerospace Institute, MIT	Defense Acquisition Projects
Former Project Manager	NASA Glenn Research Center	Fluids and Combustion Facility on Station
Cost Estimation, NASA ESMD	NASA HQ	Constellation Project
Associate Administrator, Acquisition	NASA HQ	NASA-wide
Supportability, Operability, Affordability System Integration Group Lead	NASA HQ	Constellation Project
Manager, Exploration Systems Analysis	NASA HQ	Ongoing ESMD Architectures
Section Manager General and Project Accounting	NASA JPL	JPL-wide
Supervisor, Flight Hardware Logistics Program (FHLP)	NASA JPL	JPL FHLP
Manager, FHLP	NASA JPL	JPL FHLP
Procurement Acquisition Manager	NASA JPL	Jupiter Icy Moons Orbiter
JPL Acquisition Team	NASA JPL	JPL Flight Hardware Logistics Program
Environmental Systems Lead	NASA JSC	Altair Lunar Lander
Former Chief Operating Officer	Rolls Royce North America	GE-Rolls Royce joint work on F136 engine for F-35
Colonel (ret)	USAF	USAF Space Acquisitions

APPENDIX B: DETAILED ANALYSIS OF ACQUISITION STRUCTURES

Architecture Level Strategy: Multiple Primes

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(I) Splitting the work over several primes means workload on each is less
Effective over development times of at least a decade	(I) Proven reasonably effective on (eg) Saturn LV
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	(I) NASA works closely with contractors
Give NASA confidence in contractor reliability	(I) NASA works closely with contractors
Give System integrator(s) enough HSF experience	(U) NASA may spend all its time managing contracts and lose system engineering skills
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	(U) May run into similar "silo-ing" problems as ISS
Allocate some work across all ten NASA centers	(I) Each center can help manage a prime
Robust to year-by-year changes in funding	(I) This system has delivered space systems with fluctuating funding before
Allow work to be divided between the major contractors	
Allow international partners to fit into the acquisition over time	(I) Primes come and go as new projects start, so internationals could be included
Allow commercial space companies to fit in over time.	(I) Prime contracts could be replaced with commercial services over time

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Primes will have cost and reliability targets to meet, so will try to reuse where possible	High cost systems with clear comm potential	(W) Primes have no incentive to develop a system which is common with other primes. There are concerns of liability and proprietary information.	Many systems / components	(W) Primes do not have visibility across the work of other primes. This reduces the number of systems that can be planned forward. NASA and the prime are most concerned with interfaces, rather than matching common systems.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	(U) Primes will have requirements for their system, but historically these can change drastically	Functions and constraints of potential common systems	(W) Primes are unlikely to see outside their own system	Functions and constraints of potential common systems	(W) Primes are unlikely to see outside their own system
		Form / function of existing systems	(W) The Primes will only have exposure to systems they (or their subcontractors) have designed in the past	N/A		N/A	
		Requirements from interconnected systems	(I) Primes are good at system engineering across their work package	Requirements from interconnected systems	(U) Primes have a good understanding of their own interconnected systems, but no understanding of the internal system engineering of other primes	Requirements from interconnected systems	(U) Primes have a good understanding of their own interconnected systems, but no understanding of the internal system engineering of other primes
	Process	Assess performance difference	(I) Primes are good at this, but need to be incentivized to make performance-cost trades where necessary	Identify functional similarity / difference	(W) Primes do not see the functional requirements of the building block in other systems.	Identify functional similarity / difference	(W) Primes do not see the functional requirements of the building block in other systems.
		Perform systems engineering		Perform systems engineering	(I) Primes are capable of doing the system engineering on their own system, but cannot touch the other system	Perform systems engineering	(I) Primes are capable of doing the system engineering on their own system, but cannot touch the other system
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	(I) Primes are likely to have good cost data on their systems, and will be able to get use case from NASA. Firm requirements help use case.	Anticipated use case for all new systems	(W) Primes have no access to the lifecycle cost of other systems. May have use case from NASA architecture.	Anticipated use case for all new systems	(W) Primes have no access to the lifecycle cost of other systems. May have use case from NASA architecture.
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle.	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle. Hampered by lack of inputs.	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle. Hampered by lack of inputs.
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	Low incentive to identify/evaluate new opportunities because no lifecycle responsibility
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(W) Cannot see other family members.	Effect of divergence on other family members	(W) Cannot see other family members.
	Process	Manufacture / Modify existing system	(W) Primes may not have access to IP for reuse; may be concerned about liability	Manufacture / Modify existing system	(W) Which prime manufactures? Who takes liability for error / responsibility for lateness/cost?	Manufacture mostly common systems	(W) Which prime manufactures? Who takes liability for error / responsibility for lateness/cost?
		Manage divergence	No incentive to manage divergence	Manage divergence	No incentive to manage divergence	Manage divergence and convergence	No incentive to manage divergence; no incentive to find convergence.
		Incremental Improvements to Strategy	Firm requirements Architecture-wide knowledge repository Strong commonality team	Incremental Improvements to Strategy	Incentives IP protection Good system engineering	Incremental Improvements to Strategy	

Broad acquisition considerations	
Acquisition Affordability	This is a standard acquisition structure, so the affordability is unlikely to be different from space systems in the past.
Political Risk	Low
Regulatory Feasibility	This structuer is tried and tested. There would be very little regulatory resistance.
Additional comments	

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

Architecture Level Strategy: NASA with assistance from SETA

Note: *Assumes system integrator is incentivized towards affordability goals*

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(I) Work split between primes; system integrator takes some responsibility too
Effective over development times of at least a decade	(I) System integrator is a more subtle role than lead prime, and less likely to be politically troublesome. Also easier to replace.
Deliver first flight within a decade	(I) This removes bottlenecks at the prime level by having multiple primes, and NASA level by having an assistant integrator. Likely to be expensive, however.
Allow NASA to impart its HSF experience to contractor	NASA is in some contact with the contractors; it may even be able to focus more on engineering and less on system engineering
Give NASA confidence in contractor reliability	NASA is in some level of contact with contractors
Give System integrator(s) enough HSF experience	(U) The system integrator will have HSF experience, however they will tend to lose that experience over time as they focus more on project management than production.
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	(U) System integrator may act as a go-between to smooth any inter-center rivalries
Allocate some work across all ten NASA centers	NASA still has a large amount of work under this structure so most centers will not have work drops
Robust to year-by-year changes in funding	(W) High overhead costs for each built element because of the three layers of oversight. May mean funding drops cause more funding drops because less can be built each year.
Allow work to be divided between the major contractors	There are still multiple primes taking on work.
Allow international partners to fit into the acquisition over time	
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Individual primes will be interested in cost/reliability up-front benefits.	High cost systems with clear comm potential	(I) System integrator is incentivized to look across the whole family. Assuming system integrator has authority to tweak requirements and contracts (closer to a prime) then it can effectively enforce the family view.	Many systems / components	(I) System integrator is incentivized to look across the whole family. Assuming system integrator has authority to tweak requirements and contracts (closer to a prime) then it can effectively enforce the family view.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system		Functions and constraints of potential common systems	(I) System integrator can communicate this	Functions and constraints of potential common systems	(I) System integrator can communicate this
		Form / function of existing systems	Generally old designs suitable for reuse are not more likely to come out due to system integrator	N/A		N/A	
		Requirements from interconnected systems	(I) System integrator can provide this information	Requirements from interconnected systems	(I) System integrator can communicate this	Requirements from interconnected systems	
	Process	Assess performance difference	Primes can perform this function. Up-front cost/reliability is probably enough to incentivize this.	Identify functional similarity / difference	Primes can perform this function. May need additional lifecycle cost incentives to achieve this (or give the system integrator authority to direct the prime, and incentivize the system integrator)	Identify functional similarity / difference	Primes can perform this function. May need additional lifecycle cost incentives to achieve this (or give the system integrator authority to direct the prime, and incentivize the system integrator)
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	System integrator should be responsible for lifecycle costs and use cases.	Anticipated use case for all new systems	(I) System integrator can communicate this and track lifecycle costs	Anticipated use case for all new systems	(I) System integrator can communicate this and track lifecycle costs
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle.	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle.	Evaluate commonality benefits and detriments	(U) Good at evaluating design / manufacture costs. No incentive to look at full lifecycle.
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	If incentivized by the integrator then primes will do this. Integrator may even take this task itself
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(I) System integrator can communicate this	Effect of divergence on other family members	(I) System integrator can communicate this
	Process	Manufacture / Modify existing system	(U) Primes may not have access to IP for reuse; may be concerned about liability	Manufacture / Modify existing system	(W) Which prime manufactures? Who takes liability for error / responsibility for lateness/cost?	Manufacture mostly common systems	(W) Which prime manufactures? Who takes liability for error / responsibility for lateness/cost?
		Manage divergence	No incentive to manage divergence	Manage divergence	(I) System integrator can manage divergence	Manage divergence and convergence	(I) System integrator can manage divergence
		Incremental Improvements to Strategy	Lifecycle cost incentive	Incremental Improvements to Strategy	System inttegrator must have significant authority	Incremental Improvements to Strategy	
					System integrator / NASA may need GFE type solution		

Broad acquisition considerations	
Acquisition Affordability	(U) The sole prime will realize synergies and management efficiencies, but the lack of effective competition may lead to poor cost, performance or schedule results.
Political Risk	(W) There is high political risk. Primes not chosen will likely encourage Congressional investigation of the winning bids.
Regulatory Feasibility	(W) It will be difficult to guarantee the role of the prime over this time period without re-competing the contract. Policy changes may trigger a rebid of the contract.
Additional comments	Interviewees suggested the prime contractor should not be allowed to allocate work to itself. Also, lifecycle cost incentives may be difficult because the prime is likely to collect all the information required for assessing lifecycle costs.

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

Architecture Level Strategy: Single TSPR Prime

Note: *Assumes the prime has at least development cost/schedule incentives*

NASA Acquisition Requirements	
Fund research and development	▨
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(U) This is significant work for a single prime to take on. It is probably a more difficult integration task than anything previously.
Effective over development times of at least a decade	(W) Market forces (mergers, takeovers, industry changes) could affect the prime contractor in less than a decade. So could changes of administration or Congress which cancel the contract for political reasons.
Deliver first flight within a decade	▨
Allow NASA to impart its HSF experience to contractor	(W) NASA is an extra step removed from the "actual engineering" under this structure
Give NASA confidence in contractor reliability	
Give System integrator(s) enough HSF experience	(U) The system integrator will have HSF experience, however they will tend to lose that experience over time as they focus more on project management than production.
Balance between architectural up-front and recurring costs.	▨
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	(W) The center with responsibility for managing the prime will be busy while others are quieter. The lack of work may create fights to keep turf.
Allocate some work across all ten NASA centers	(W) Likely to decrease total NASA workload, and assign one center as a project mangement hub, while others focus more on R&D
Robust to year-by-year changes in funding	▨
Allow work to be divided between the major contractors	(W) Heavily biases the work towards one prime contractor.
Allow international partners to fit into the acquisition over time	(U) NASA has less control over who builds what; at the same time, the more commercial structure favors the lower bidders with less regard for nationality.
Allow commercial space companies to fit in over time.	(U) NASA has less control over the integration of commercial space companies, and competitive pressures may keep them out; however if their product is truly better the prime is likely to award them the contract.

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Assuming some cost / schedule incentives, prime is likely to encourage cost / reliability reuse over corporations seeking new developments if the existing will do.	High cost systems with clear comm potential	(I) Assuming cost / schedule incentives from NASA as customer, prime can look over whole exploration architecture and develop building block strategies. Needs consistent, fixed requirements from NASA.	Many systems / components	(I) Prime can achieve this with adequate incentives. Likely to still overstate benefits at outset (eg JSF). Incentives should cover full lifecycle.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system		Functions and constraints of potential common systems	(I) Prime is likely to be in charge over full architecture development. If incentivized, prime could look forward to future functions.	Functions and constraints of potential common systems	(I) Prime is likely to be in charge over full architecture development. If incentivized, prime could look forward to future functions.
		Form / function of existing systems	(U) The sole prime loses NASA's historical perspective on good designs. Reuse from other parts of the system is likely to be encouraged.	N/A		N/A	
		Requirements from interconnected systems	(I) The sole prime is relatively good at managing the systems engineering communication	Requirements from interconnected systems	(I) The sole prime is relatively good at managing the systems engineering communication	Requirements from interconnected systems	(I) The sole prime is relatively good at managing the systems engineering communication
	Process	Assess performance difference	(I) With incentives, the sole prime is able to undertake this.	Identify functional similarity / difference	(I) With incentives, the sole prime is able to undertake this.	Identify functional similarity / difference	(I) With incentives, the sole prime is able to undertake this.
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	(U) Prime may be less concerned about lifecycle costs unless it is incentivized.	Anticipated use case for all new systems	(I) Prime develops use case and cost analysis for all systems	Anticipated use case for all new systems	(I) Prime develops use case and cost analysis for all systems
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments	(I) Assuming inputs are available, the prime will be relatively good at evaluation	Evaluate commonality benefits and detriments		Evaluate commonality benefits and detriments	
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	(I) With incentives, the sole prime is able to undertake this.	Evaluate if commonality is beneficial	(I) With incentives, the sole prime is able to undertake this.
Implement	Inputs	N/A		N/A		Continuous Identify	(I) Prime will perform these tasks if likely incentive payoffs outweigh management costs
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(I) Sole prime is likely to be able to assess divergence impacts across the architecture	Effect of divergence on other family members	(I) Sole prime is likely to be able to assess divergence impacts across the architecture
	Process	Manufacture / Modify existing system	(W) May be difficult for prime to secure reuse rights with limited NASA involvement and competitive pressures from original designer.	Manufacture / Modify existing system	(I) IP will be generated during the time the prime is in control and therefore can be planned for	Manufacture mostly common systems	(I) IP will be generated during the time the prime is in control and therefore can be planned for
		Manage divergence	Will manage divergence if incentivized to do so	Manage divergence	(I) Divergence will impact up-front cost on future systems, therefore prime likely to control it.	Manage divergence and convergence	(I) Divergence will impact up-front cost on future systems, therefore prime likely to control it.
		Incremental Improvements to Strategy	Incentives on cost / schedule / reliability	Incremental Improvements to Strategy	Incentives on cost / schedule / reliability	Incremental Improvements to Strategy	Full lifecycle cost incentives
			Incentives on lifecycle cost		Incentives on lifecycle cost		
			Wide IP rights for NASA, passed through to sole prime.				

Broad acquisition considerations	
Acquisition Affordability	(U) The sole prime will realize synergies and management efficiencies, but the lack of effective competition may lead to poor cost, performance or schedule results.
Political Risk	(W) There is high political risk. Primes not chosen will likely encourage Congressional investigation of the winning bids.
Regulatory Feasibility	(W) It will be difficult to guarantee the role of the prime over this time period without re-competing the contract. Policy changes may trigger a rebid of the contract.
Additional comments	Interviewees suggested the prime contractor should not be allowed to allocate work to itself. Also, lifecycle cost incentives may be difficult because the prime is likely to collect all the information required for assessing lifecycle costs.

KEY
🟩 (I) Process / Input likely to be achieved
🟨 (U) Uncertain whether process / input will be achieved
🟥 (W) Uncertain whether process / input will be achieved
▨ No effect

Architecture Level Strategy: Commercial and NASA in Alliance

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(U) Only one or two prime contractors at most under this structure. High workload for those companies.
Effective over development times of at least a decade	(U) This is roughly double the duration of a usual alliance contract - but that does not necessarily make it unworkable.
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	(I) Contractor and NASA work extremely closely under this structure
Give NASA confidence in contractor reliability	(I) Contractor and NASA work extremely closely under this structure
Give System integrator(s) enough HSF experience	(I)System integrator likely to be a blend of NASA and contractor personnel
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	(U) Contractor will take significant risk, which may require private funding
Allow corporations to make a profit on small projects	Subcontractors under the alliance will still be able to be funded
Overcome inter-center parochialism.	
Allocate some work across all ten NASA centers	
Robust to year-by-year changes in funding	(U) NASA and contractor will share the impact of funding changes, so may be robust. However, contractor must first accept the risks of project funding cancellation.
Allow work to be divided between the major contractors	Subcontractors under the alliance will still be able to be funded
Allow international partners to fit into the acquisition over time	(W) The alliance ties together NASA and the contractor very tightly. There could be provisions for international partners to join, but this would probably require a lot of management rework. Possible for internationals to join as subcontractors.
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Assuming some cost / schedule incentives, both prime and NASA are likely to encourage cost / reliability reuse	High cost systems with clear comm potential	(I) NASA will push partners / contractors to realize cost / performance over product lifecycle.	Many systems / components	(I) NASA will push partners / contractors to realize cost / performance over product lifecycle.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system		Functions and constraints of potential common systems	(I) NASA / Prime alliance can gather information on systems	Functions and constraints of potential common systems	(I) NASA / Prime alliance can gather information on systems
		Form / function of existing systems	(I) NASA can contribute its knowledge on existing systems.	N/A		N/A	
		Requirements from interconnected systems	(I) The sole prime is relatively good at managing the systems engineering communication	Requirements from interconnected systems	(I) Prime and NASA both skilled in system engineering / requirements communication	Requirements from interconnected systems	(I) Prime and NASA both skilled in system engineering / requirements communication
	Process	Assess performance difference	(I) With incentives, the sole prime is able to undertake this.	Identify functional similarity / difference	(I) Prime and NASA both skilled in system engineering / requirements communication	Identify functional similarity / difference	(I) Prime and NASA both skilled in system engineering / requirements communication
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	(I) NASA will be concerned with lifecycle costs and help with modeling	Anticipated use case for all new systems	(I) NASA has long-range view of systems to perform lifecycle cost and use case studies	Anticipated use case for all new systems	(I) NASA has long-range view of systems to perform lifecycle cost and use case studies
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments	(I) Assuming inputs are available, the prime will be relatively good at evaluation	Evaluate commonality benefits and detriments	(I) Assuming inputs are available, the prime will be relatively good at evaluation	Evaluate commonality benefits and detriments	(I) Assuming inputs are available, the prime will be relatively good at evaluation
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(I) The alliance will incentivize these if necessary
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(I) The alliance has visibility over other family members and can assess divergence	Effect of divergence on other family members	(I) The alliance has visibility over other family members and can assess divergence
	Process	Manufacture / Modify existing system	(U) NASA will need to acquire IP rights for the reuse	Manufacture / Modify existing system	IP will be created during project, Alliance will need to decide who manufactures	Manufacture mostly common systems	IP will be created during project, Alliance will need to decide who manufactures
		Manage divergence	(I) Up-front cost-reliability benefits motivate minimizing divergence	Manage divergence	(I) Overall alliance perspective on lifecycle costs incentivizes minimizing divergence	Manage divergence and convergence	(I) Overall alliance perspective on lifecycle costs incentivizes minimizing divergence
		Incremental Improvements to Strategy	Strong negotiation of IP rights	Incremental Improvements to Strategy		Incremental Improvements to Strategy	

Broad acquisition considerations	
Acquisition Affordability	(U) When alliance contracts work, they perform well. However, when they fail they usually turn spectacularly wrong. This approach would be a gamble by NASA.
Political Risk	(W) High political risk. This strategy has not been used before for space acquistiions, and Congress will likely blame the alliance structure in hindsight if it fails.
Regulatory Feasibility	(W) This structure does not appear to have been tried in US Government Contracting. It will probably meet significant resistance.
Additional comments	

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Structure: Fully Competitive

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(I) Selected contractors are likely to be competent.
Effective over development times of at least a decade	
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	
Give NASA confidence in contractor reliability	(U) Changing contractors makes reliability difficult
Give System integrator(s) enough HSF experience	
Balance between up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	
Allocate some work across all ten NASA centers	
Robust to year-by-year changes in funding	
Allow work to be divided between the major contractors	🟩
Allow international partners to fit into the acquisition over time	
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Up-front cost / reliability is likely to incentivize contractors to consider some reactive reuse	High cost systems with clear comm potential	(W) No visibility across the rest of the product family or lifecycle	Many systems / components	(W) No visibility across the rest of the product family or lifecycle
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	(I) Contractor can see its own requirements	Functions and constraints of potential common systems	(W) No visibility	Functions and constraints of potential common systems	(W) No visibility
		Form / function of existing systems	(W) Contractor is unlikely to have a good view of many existing systems	N/A		N/A	
		Requirements from interconnected systems	(I) Contractor can see its own interconnected systems	Requirements from interconnected systems	(W) Contractor cannot see other interconnected systems	Requirements from interconnected systems	(W) Contractor cannot see other interconnected systems
	Process	Assess performance difference	Contractor is capable of making this trade	Identify functional similarity / difference	Assuming it had the inputs, contractor is capable of making this trade	Identify functional similarity / difference	Assuming it had the inputs, contractor is capable of making this trade
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	(U) The contractor may not have enough information about the use case or lifecycle cost to undertake analysis	Anticipated use case for all new systems	(W) No visibility	Anticipated use case for all new systems	(W) No visibility
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments	(I) Contractor is capable of making this trade, incentivized by up-front cost/ reliability	Evaluate commonality benefits and detriments	Contractor is capable of making this trade	Evaluate commonality benefits and detriments	Contractor is capable of making this trade
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(W) No incentive or inputs to do so
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(W) No visibility	Effect of divergence on other family members	(W) No visibility
	Process	Manufacture / Modify existing system	(W) Primes may not have access to IP for reuse; may be concerned about liability	Manufacture / Modify existing system	(W) If prime manufactures building block, is it comfortable giving away IP? Will other contractors accept it instead of undertaking their own design? Would benefit from strong NASA Sys Eng / Commonality teams	Manufacture mostly common systems	(W) If prime manufactures building block, is it comfortable giving away IP? Will other contractors accept it instead of undertaking their own design? Would benefit from strong NASA Sys Eng / Commonality teams
		Manage divergence	(I) Incentivized to manage divergence to the extent it affects cost / reliability	Manage divergence	(W) Incentivized to sacrifice commonality for performance in their own individual systems	Manage divergence and convergence	(W) Incentivized to sacrifice commonality for performance in their own individual systems
		Incremental Improvements to Strategy	Centralized knowledge repository Good systems engineering IP Provisions Incentives for up-front cost / reliability like fixed price	Incremental Improvements to Strategy	The fully competitive strategy is not a good starting point for building block commonality so no improvements were considered.	Incremental Improvements to Strategy	The fully competitive strategy is not a good starting point for building block commonality so no improvements were considered.

Broad acquisition considerations	
Acquisition Affordability	
Political Risk	🟩
Regulatory Feasibility	🟩
Additional comments	

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Strategy: Joint Venture

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	(I) JV increases resources
Effective over development times of at least a decade	(U) JVs are more likely to fragment than sole companies
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	
Give NASA confidence in contractor reliability	(U) JV creates new culture, risk of quality changes; however can also pool knowledge
Give System integrator(s) enough HSF experience	
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	(I) JV allow two companies to survive even if market wouldn't support them independently
Overcome inter-center parochialism.	
Allocate some work across all ten NASA centers	(W) The JV will only be managed by a single center when previously its members might have been managed by two.
Robust to year-by-year changes in funding	
Allow work to be divided between the major contractors	(I) Spreads work across two contractors
Allow international partners to fit into the acquisition over time	
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components		High cost systems with clear comm potential	JV not incentivized to look forward across the lifecycle without cost incentive	Many systems / components	(I) JV can identify commonality within its own systems well. Has little incentive to look for it though under a cost-plus style contract.
		Up front cost / reliability improvements	(I) JV likely to look for up-front cost / reliability savings, esp if fixed $	Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	Depends on customer	Functions and constraints of potential common systems	(I) JV is likely to be in a monopoly position so comfortable to look forward to future systems.	Functions and constraints of potential common systems	JV is likely to obtain future work, but cannot see outside its own system
		Form / function of existing systems	(I) JV has good visibility across its members' products	N/A		N/A	
		Requirements from interconnected systems	(I) Relies on system engineering, improved if JV does system eng	Requirements from interconnected systems	(I) Relies on system engineering, improved if JV does system eng	Requirements from interconnected systems	JV unlikely to take on system engineering outside its own systems
	Process	Assess performance difference	(I) JV will identify commonalities to realize up-front cost savings but will not go further in the lifecycle	Identify functional similarity / difference	JV not incentivized to look forward across the lifecycle without cost	Identify functional similarity / difference	JV not incentivized to look forward across the lifecycle without cost incentive
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	Depends on system engineering	Anticipated use case for all new systems		Anticipated use case for all new systems	
		Lifecycle cost estimate of unique new system	(I) JV should be able to estimate unique cost	Unique lifecycle cost of all new systems	No incentive to look forward to future systems	Unique lifecycle cost of all new systems	No incentive to look forward to future systems
	Process	Evaluate commonality benefits and detriments	JV is capable of these steps, but needs incentive to undertake them	Evaluate commonality benefits and detriments		Evaluate commonality benefits and detriments	
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(U) No incentive to continually identify / evaluate, but no barriers to it within the system
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	No incentive to look forward to future systems	Effect of divergence on other family members	(I) JV has a good view of the impact of divergence within its own system. Good sys eng helps expand this view.
	Process	Manufacture / Modify existing system	(U) JV should have the IP and liability for the system; but shared use could be contested without strong NASA negotiators.	Manufacture / Modify existing system	(I) Prevents two completely different systems from being used; however unlikely to be true building blocks, closer to common subcontractor outcome	Manufacture mostly common systems	(U) JV not incentivized to manage divergence if cost plus
		Manage divergence	No incentive to manage divergence	Manage divergence	No incentive to manage divergence.	Manage divergence and convergence	
		Incremental Improvements to Strategy	JV to include system engineering if possible JV to be across wide range of systems JV needs incentive to reuse Strong commonaltiy team	Incremental Improvements to Strategy	JV incentive to look across full lifecycle JV incentive to look forward to future systems	Incremental Improvements to Strategy	JV incentive to look across full lifecycle JV incentive to look forward to future systems

Broad acquisition considerations	
Acquisition Affordability	(U) The JV may decrease competition and therefore increase prices. It may also reduce duplication of effort and management overheads. Good system engineering and insight from NASA will reduce the drawbacks from a lack of competition, but NASA time and resources decrease affordability.
Political Risk	(U) Creating or allowing JVs will attract attention from policiticians and industry groups. There is an element of political risk.
Regulatory Feasibility	It is feasible to use JVs as acquisition strategies. The JV should only be used where the market is willing to form the JV without pressure from NASA
Additional comments	The JV is of limited use because of the few times it can be used. However, it is an effective commonality vehicle if it is combined with the right incentive structure.

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Strategy: Directed Contractor

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	
Effective over development times of at least a decade	(W) It is difficult to repeatedly direct a subcontractor over these time periods
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	(I) NASA's previous work with this subcontractor will be retained
Give NASA confidence in contractor reliability	(I) NASA has previously worked with this contractor and is confident in output
Give System integrator(s) enough HSF experience	
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	
Allocate some work across all ten NASA centers	(U) Retaining an existing contractor makes it likely the supervisory work will be done by the same NASA center, but this may not be widespread
Robust to year-by-year changes in funding	
Allow work to be divided between the major contractors	(W) Retaining an existing contractor reduces the chance for other contractors to participate
Allow international partners to fit into the acquisition over time	(W) If the initial subcontractors are US, makes it harder for internationals to break in
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) A subcontractor is likely to see benefit in reusing its own designs; it has visibility, and reliability, at least, as an incentive (cost also under fixed price contract)	High cost systems with clear comm potential	(U) Directed subcontractor can look back in time at previous projects but cannot look forward because it is only engaged to work on a single system at a time.	Many systems / components	(U) Can only operate on the systems / components which are in its system; no incentive to look forward; low barriers to forward planning though.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	(I) The directed subcontractor has good visibility into its own designs and the new requirements.	Functions and constraints of potential common systems	(W) Directed subcontractor cannot look forward to potential common systems.	Functions and constraints of potential common systems	(W) Directed subcontractor cannot look forward to potential common systems.
		Form / function of existing systems		N/A		N/A	
		Requirements from interconnected systems	(W) The structure doesn't assist with performance-cost trades across subcontractor-prime boundaries.	Requirements from interconnected systems	(W) The structure doesn't assist with performance-cost trades across subcontractor-prime boundaries.	Requirements from interconnected systems	(W) The structure doesn't assist with performance-cost trades across subcontractor-prime boundaries.
	Process	Assess performance difference	(I) Subcontractor should be well placed to assess its previous design	Identify functional similarity / difference	(W) Subcontractor is chosen to do a new design based on its existing design, preventing it from identifying the best building block over future systems	Identify functional similarity / difference	(U) Subcontractor cannot look forward, but can do system engineering within its own systems.
		Perform systems engineering	Subcontractor can't go outside its own system to do sys eng trade	Perform systems engineering		Perform systems engineering	
		Assess modifying existing item	(I) Subcontractor should be well placed to assess modification cost	Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	Requires good system engineering	Anticipated use case for all new systems	(W) Subcontractor unlikely to develop a system that looks forward to new future systems	Anticipated use case for all new systems	(W) Subcontractor unlikely to develop a system that looks forward to new future systems
		Lifecycle cost estimate of unique new system	(I) Subcontractor should be well placed to assess unique cost	Unique lifecycle cost of all new systems	(I) Subcontractor could consider future costs if incentivized to	Unique lifecycle cost of all new systems	(I) Subcontractor could consider future costs if incentivized to
	Process	Evaluate commonality benefits and detriments	(U) Subcontractor has most of the information to do this, but is not incentivized to consider beyond its own involvement in the lifecycle.	Evaluate commonality benefits and detriments	(W) Directed subcontractor is likely to concentrate on the particular instance, rather than weighting across the whole family.	Evaluate commonality benefits and detriments	(W) Directed subcontractor is likely to concentrate on the particular instance, rather than weighting across the whole family.
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(U) No incentive to continually identify / evaluate, but no barriers to it within the system
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	May be able to assess impact of divergence on existing system, but not future systems	Effect of divergence on other family members	
	Process	Manufacture / Modify existing system	(I) Subcontractor already has all the IP and liability for the system.	Manufacture / Modify existing system	(U) Subcontractor already has all the IP and liability for the system. However, without incentives a common subcontractor is unlikely to produce common systems	Manufacture mostly common systems	(W) Systems likely to change for future systems due to bias towards current variant. No incentive to mange divergence.
		Manage divergence	(U) Subcontractor not incentivized to manage divergence if cost plus	Manage divergence	(W) Constantly biased towards current variant	Manage divergence and convergence	
		Incremental Improvements to Strategy	Fixed price contract Good sys eng,	Incremental Improvements to Strategy	Directed subcontractor is not a good strategy for developing common building blocks if the systems which use the building blocks are offset significantly in time	Incremental Improvements to Strategy	Directed subcontractor is not a good strategy for developing widespread forward commonality as there is no forward-looking component

Broad acquisition considerations	
Acquisition Affordability	(U) Relationship with directed contractor must be carefully managed because the contractor can be in a monopoly position. Difficult to tell whether efficiencies from single contractor outweigh the lifting of market price pressures.
Political Risk	(W) Directing particular subcontractors favors the incumbent contractors and so it is open to political attack. Also appears as if the government is interfering in the supply chain of the prime.
Regulatory Feasibility	(W) Specification of particular contractors is achieved by writing a "sole source justification" but these are the exception not the rule. Recompetition after a couple of years is usually necessary, and exploration architectures take longer than that to develop.
Additional comments	Implementation of a directed subcontractor arrangement raises issues of responsibility between government and prime contractor. May consume management time or sour relationship between government and prime.

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Strategy: Long-Term Supplier

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	
Effective over development times of at least a decade	(W) There is a risk the specialist contractor will politically forced to share work, be unable to perform or leave the industry
Deliver first flight within a decade	(I) Learning benefits should make work faster
Allow NASA to impart its HSF experience to contractor	(I) NASA's previous work with this subcontractor will be retained
Give NASA confidence in contractor reliability	(I) NASA has previously worked with this contractor and is confident in output
Give System integrator(s) enough HSF experience	
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	(U)Winning contractor has a long term revenue stream; however also reduces competition, which may send some contractors out of the industry.
Overcome inter-center parochialism.	(U) A specialist subcontractor would have multiple centers working with the specialist over time. This could increase cooperation or create more friction between centers.
Allocate some work across all ten NASA centers	(W) Retaining an existing contractor makes it likely the supervisory work will be done by the same NASA center
Robust to year-by-year changes in funding	
Allow work to be divided between the major contractors	(W) If on a major system, reduces the chance for other contractors to participate
Allow international partners to fit into the acquisition over time	(W) If the initial subcontractors are US, makes it harder for internationals to break in
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	(I) Specialist has good visibility over previous projects	High cost systems with clear comm potential	(I) High cost systems with common potential are the type that a specialist would be created for. Infrequent entry works well with the high cost of setting up a specialist.	Many systems / components	(I) Within its own system, the specialist can plan commonality for the future. This may miss more widespread commonality though.
		Up front cost / reliability improvements	(U) Depends on risk-reward profile (how risk averse is specialist?)	Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture	(I) Both possible with specialist	Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	(I) Specialist can see its own requirements	Functions and constraints of potential common systems	(I) Specialist knows it will obtain future work and therefore can demand / act on information on future systems	Functions and constraints of potential common systems	(U) Specialist knows it will obtain future work and therefore can demand / act on information on future systems. However cannot see outside its own system
		Form / function of existing systems	(I) Specialist has good visibility over its own previous projects	N/A		N/A	
		Requirements from interconnected systems	Depends on quality of system engineering	Requirements from interconnected systems	Depends on quality of system engineering	Requirements from interconnected systems	Depends on quality of system engineering
	Process	Assess performance difference	(I) Specialist should be well placed to assess its previous design	Identify functional similarity / difference	(I) Specialist can assess future systems as it has insight into them	Identify functional similarity / difference	(U) As for common building block, but with additional drawback that specialist may not be incentivized to develop the recurring, continuous evaluation of commonality needed.
		Perform systems engineering	Specialist can't go outside its own system to do sys eng trade	Perform systems engineering	Specialist can't go outside its own system to do sys eng trade	Perform systems engineering	
		Assess modifying existing item	(I) Specialist should be well placed to assess modification cost	Assess modifying particular instances	(I) Specialist should be well placed to assess modification cost	Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system	Depends on quality of system engineering	Anticipated use case for all new systems	Depends on quality of system engineering	Anticipated use case for all new systems	Depends on quality of system engineering
		Lifecycle cost estimate of unique new system	(I) Specialist should have the engineering detail to assess this	Unique lifecycle cost of all new systems	(I) Specialist should have the engineering detail to assess this	Unique lifecycle cost of all new systems	(I) Specialist should have the engineering detail to assess this
	Process	Evaluate commonality benefits and detriments	Specialist is capable of doing this, but needs incentive to evaluate the full lifecycle rather than just its own design / manufacture phase.	Evaluate commonality benefits and detriments	(I) Specialist will evaluate the development cost benefits over all the elements in the system. Still requires incentives to evaluate full lifecycle	Evaluate commonality benefits and detriments	(U) As for common building block, but with additional drawback that specialist may not be incentivized to develop the recurring, continuous evaluation of commonality needed.
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(U) Needs incentives to do this that may not be present otherwise.
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(I) Specialist can look forward to impact of divergence on future systems	Effect of divergence on other family members	(I) Specialist has a good view of the impact of divergence within its own system. Good sys eng helps expand this view.
	Process	Manufacture / Modify existing system	(I) Specialist already has all the IP and liability for the system.	Manufacture / Modify existing system	(U) Specialist already has all the IP and liability for the system. However, without incentives a common subcontractor is unlikely to produce common systems	Manufacture mostly common systems	(U) Specialist not incentivized to manage divergence if cost plus
		Manage divergence	(U) Specialist not incentivized to manage divergence if cost plus	Manage divergence	(U) Specialist not incentivized to manage divergence if cost plus	Manage divergence and convergence	
		Incremental Improvements to Strategy	Fixed cost contracts	Incremental Improvements to Strategy	Firm requirements	Incremental Improvements to Strategy	Firm requirements
			Incentives to consider reuse		Good system engineering		Good system engineering
			Good system engineering		Incentives to develop building block		Incentives to assess full lifecycle commonality impact
					Incentives to manage divergence		Incentives to manage divergence

Broad acquisition considerations	
Acquisition Affordability	(U) Relationship with specialist subcontractor must be carefully managed because the contractor can be in a monopoly position. Difficult to tell whether efficiencies from single contractor outweigh the lifting of market price pressures. Leader-follower contracts are an option here to increase cost but reduce risk.
Political Risk	(W) The idea of a specialist subcontractor over acquisition timeframes of decades is likely to provoke significant debate in NASA Senate / Congressional hearings.
Regulatory Feasibility	(W) The lack of competition in this structure would make it a difficult structure to get through the FAR
Additional comments	

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Strategy: Build-to-Print

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	
Prime contractors can handle complex, expensive systems	
Effective over development times of at least a decade	
Deliver first flight within a decade	
Allow NASA to impart its HSF experience to contractor	(I) NASA's specification of form implies deep input into the design
Give NASA confidence in contractor reliability	
Give System integrator(s) enough HSF experience	
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	
Allocate some work across all ten NASA centers	
Robust to year-by-year changes in funding	
Allow work to be divided between the major contractors	(I) Selecting two contractors for one system divides the work.
Allow international partners to fit into the acquisition over time	
Allow commercial space companies to fit in over time.	

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	The system integrator (requirements writer) manages the entry gateway, contractors have no choice	High cost systems with clear comm potential	The system integrator manages the entry gateway, contractors have no choice	Many systems / components	(W) The structure is too administratively cumbersome to set up each time a commonality opportunity needs to be investigated. Therefore unsuitable for widespread commonality.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	(I) The contractor is given direct insight into the system that is to be made common through the specification of form. Assumes system integrator has correctly identified commonality	Functions and constraints of potential common systems	(U) The contractor is given direct insight into the system that is to be made common. Breaks down if there are any future systems that may need to use the same system and the system integrator hasn't identified them.	Functions and constraints of potential common systems	🟨
		Form / function of existing systems		N/A		N/A	🟨
		Requirements from interconnected systems		Requirements from interconnected systems		Requirements from interconnected systems	🟨
	Process	Assess performance difference	(U) The contractor is not given any latitude to perform system engineering because the form is specified. This is acceptable only if the evaluation was done at the system integrator level before requirements were written	Identify functional similarity / difference	(U) Relies on system integrator to make the cost-perfomance trades.	Identify functional similarity / difference	🟨
		Perform systems engineering		Perform systems engineering		Perform systems engineering	🟨
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	🟨
Evaluate	Inputs	Anticipated use case for new system	(U) The contractor has no latitude to perform commonality evaluation. This is acceptable only if the evaluation was done at the system integrator level before requirements were written.	Anticipated use case for all new systems	(U) The contractor has no latitude to perform commonality evaluation. This is acceptable only if the evaluation was done at the system integrator level before requirements were written.	Anticipated use case for all new systems	🟨
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems		Unique lifecycle cost of all new systems	🟨
	Process	Evaluate commonality benefits and detriments		Evaluate commonality benefits and detriments		Evaluate commonality benefits and detriments	🟨
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	🟨
Implement	Inputs	N/A		N/A		Continuous Identify	(W) There is a negative incentive for the contractor to revisit the commonality identify / evaluate processes because they cannot
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(W) The contractor has no insight into the other common system and so cannot manage divergence.	Effect of divergence on other family members	(W) The contractor has no insight into the other common system and so cannot manage divergence.
	Process	Manufacture / Modify existing system	🟩	Manufacture / Modify existing system	🟩	Manufacture mostly common systems	🟩
		Manage divergence	(W) The contractor has no appreciation for synergies with the other common system and so cannot manage divergence effectively.	Manage divergence	(W) The contractor has no insight into the other common system and so cannot manage divergence.	Manage divergence and convergence	(W) The contractor has no insight into the other common system and so cannot manage divergence.
		Incremental Improvements to Strategy	Good system engineering (identify the right opportunities) Strong commonality team (divergence)	Incremental Improvements to Strategy	Good system engineering (identify the right opportunities) Strong commonality team (divergence)	Incremental Improvements to Strategy	This is an unrealistic structure for Widespread Forward Commonality

Commonality exploration phase

Broad acquisition considerations	
Acquisition Affordability	Puts significant work on the system integrator in defining precisely the requirements and managing the contractors through development
Political Risk	Presents very low political risk
Regulatory Feasibility	Reasonably feasible, except that the FAR prefers to see major projects undertaken with function-based requirements, not form-based.
Additional comments	

KEY
(I) Process / Input likely to be achieved
(U) Uncertain whether process / input will be achieved
(W) Uncertain whether process / input will be achieved
No effect

System Level Strategy: GFE

NASA Acquisition Requirements	
Fund research and development	
Tolerate cost/schedule overruns exceeding initial estimates.	(W) Schedule slips on the GFE project will impact all other projects
Prime contractors can handle complex, expensive systems	
Effective over development times of at least a decade	(U) GFE at start may be obselete by the end of the project
Deliver first flight within a decade	(W) The GFE must be developed first, stretching the timetable.
Allow NASA to impart its HSF experience to contractor	
Give NASA confidence in contractor reliability	(I) NASA only has to become confident in GFE once.
Give System integrator(s) enough HSF experience	(I) System integrators could take on small GFE projects
Balance between architectural up-front and recurring costs.	
Not depend heavily on private funding in the product lifecycle	
Allow corporations to make a profit on small projects	
Overcome inter-center parochialism.	(U) Hardware developed by one center would be integrated into projects at other centers. This could either increase cooperation or create more friction between centers.
Allocate some work across all ten NASA centers	
Robust to year-by-year changes in funding	(W) The GFE will be on the critical path for the acquisition. It is difficult to work on other projects if the GFE is not ready. Therefore early funding cuts could slow progress.
Allow work to be divided between the major contractors	
Allow international partners to fit into the acquisition over time	(W) reduces international opportunities - initial subcontractors will be US; ITAR difficulties in sharing GFE internationally.
Allow commercial space companies to fit in over time.	(W)Commercial has fully developed projects with no need for GFE systems. Therefore the sunk cost in GFE may act as a disincentive to involve commercial companies

		Reactive reuse		Common building block		Widespread Forward Commonality	
Entry Gateway		Single systems or components	From a reuse perspective, GFE is simply a contractor developing a system. It doesn't offer any particular advantages over a competitive contract.	High cost systems with clear comm potential	(I) GFE will be used across the family, and is usually established for projects with clear commonality potential. Cost of setting up GFE structure is ok - CBB is infrequently entered.	Many systems / components	(W) GFE structure is difficult to set up for many systems, as it requires management of an additional contractor.
		Up front cost / reliability improvements		Cost/perf across whole family and lifecycle		Cost/perf across whole family and lifecycle	
		Isolated incidents or culture		Infrequently entered		Frequent, often culture	
Identify	Inputs	Requirements of proposed system	The GFE contractor is not selected for particular insight into any previous systems.	Functions and constraints of potential common systems	(U)It is relatively easy to give the GFE contractor visibility across all the potential future projects. May not have a good view of interconnected systems and associated performance-cost trade however.	Functions and constraints of potential common systems	
		Form / function of existing systems		N/A		N/A	
		Requirements from interconnected systems		Requirements from interconnected systems		Requirements from interconnected systems	
	Process	Assess performance difference	(I) There is a slight incentive towards identifying good reuse opportunities because the effort of identification by the contractor will be spread over several systems.	Identify functional similarity / difference	(I) Single contractor performing trades across all common systems helps the systems engineering process.	Identify functional similarity / difference	(W) "Continuous pursuit" of system engineering performance-cost trades cannot be done quickly because you need to go outside the "project" organization to the GFE provider
		Perform systems engineering		Perform systems engineering		Perform systems engineering	
		Assess modifying existing item		Assess modifying particular instances		Assess modifying particular instances	
Evaluate	Inputs	Anticipated use case for new system		Anticipated use case for all new systems	Requires this from the system integrator / customer	Anticipated use case for all new systems	(W) Becomes cumbersome to keep providing this outside the project organization
		Lifecycle cost estimate of unique new system		Unique lifecycle cost of all new systems	(I) As system developer, can compare unique with common	Unique lifecycle cost of all new systems	
	Process	Evaluate commonality benefits and detriments		Evaluate commonality benefits and detriments	Needs additional contractual incentives to actually make this evaluation as the customer would like; otherwise there is no guidance as to how the performance-cost trade should be made.	Evaluate commonality benefits and detriments	Needs additional contractual incentives to actually make this evaluation as the customer would like; otherwise there is no guidance as to how the performance-cost trade should be made.
		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial		Evaluate if commonality is beneficial	
Implement	Inputs	N/A		N/A		Continuous Identify	(W) Becomes cumbersome to keep providing this outside the project organization
		N/A		N/A		Continuous Evaluate	
		N/A		Effect of divergence on other family members	(I) Can easily see the direct effect of divergence on the other systems	Effect of divergence on other family members	(U) Difficult for the GFE organization to continue doing this for smaller and smaller systems
	Process	Manufacture / Modify existing system		Manufacture / Modify existing system	(W) Provision of system must deal with liability / responsibility issues.	Manufacture mostly common systems	(W) The GFE organization cannot quickly change the types of things it is expected to manufacture as new opportunities occur.
		Manage divergence		Manage divergence	(W) No incentive for GFE supplier to manage divergence, no control over design changes on other systems that propagate divergence, possible that GFE recipients may modify the GFE to optimize performance	Manage divergence and convergence	(W) No incentive to manage divergence, no control over design changes on other systems that propagate divergence; significant time offset
		Incremental Improvements to Strategy	GFE offers minimal advantages for reactive reuse	Incremental Improvements to Strategy	Firm requirements	Incremental Improvements to Strategy	GFE not a good strategy for widespread forward commonality
					Good system engineering / integrator		
					Incentive towards beneficial commo		
					Good commonality management / t		
					Liability / responsibility arrangemen		

Broad acquisition considerations	
Acquisition Affordability	Relationship with GFE contractor must be carefully managed because the contractor can be in a monopoly position. Difficult to tell whether efficiencies from single contractor outweigh the lifting of market price pressures.
Political Risk	GFE contracts can be spread around different contractors. Political risk is minimal.
Regulatory Feasibility	Need to recompete contracts is directly in conflict with wider use of GFE. NASA acquisition experts would prefer to reduce the amount of GFE provided.
Additional comments	

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