Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets

by

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Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2008

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Abstract

Commonality, or the sharing of components, processes, technologies, interfaces and/or infrastructure across a product family, represents one of many potential tools for increasing corporate profitability. Industrial interest in commonality is strong, but results appear to be mixed. A rich stream of academic research has examined commonality (typically under terms such as “product platforms” and “platform-based development”) but has not emphasized the benefits and penalties of commonality, a topic that is critical to effective product family planning and lifecycle management, and ultimately, to improving corporate profitability.

This dissertation leverages field research and a simple cost model to examine commonality in the context of complex product families. The core research effort was focused on conducting seven case studies of complex product families (aircraft, automobiles, satellites, and capital equipment). While the case studies provided a wealth of general insights, the studies were focused on examining divergence and lifecycle offsets, two critical topics that influence the benefits and penalties of commonality, yet appear to be inadequately addressed by the literature. Divergence refers to the tendency for commonality to reduce with time, for both beneficial and non-beneficial reasons. Lifecycle offsets refer to temporal differences between the lifecycle phases of product family members. Lifecycle offsets alter the potential benefits and penalties of commonality and their apportionment to individual products. Additionally, key factors identified during the literature review and case studies were translated into a simple two-product cost model of development and production in order to demonstrate key research insights in a more analytical manner.

The case studies provide a refined view of commonality that reflects the realities of industrial practice. The cases indicate that complex product families are developed in a mostly sequential manner; that commonality is highest during the product family planning phase and then declines significantly throughout the lifecycle; and that development focuses more on reusing prior product baselines than on enabling future, potential commonality. The case studies also identified challenges in the evaluation of commonality and its lifecycle management. The case findings and simple cost model contribute to an improved understanding of commonality, while the recommendations offer potential paths to improved corporate profitability.

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To Amy, Evelyn, and Sadie

Acknowledgements

First and foremost, I want to thank my family as I could not have completed this degree without their support and understanding. Amy, my wife, willingly gave much, much more than I could have asked of her. She has an amazing inner strength and a personality that I truly admire. I am grateful for her support, understanding, friendship, and love. I am also grateful for my two wonderful daughters, Evelyn and Sadie. Both have given up time with me in order to allow me to complete this degree. While Sadie is an infant, Evelyn is three years old and always supported this process in a way that was beyond her years. I would also like to thank our extended family for their support and encouragement.

My committee members have been extremely helpful to me during my time at MIT. I would like to thank my advisor, Ed Crawley, for providing significant guidance and funding during my doctoral program. Ed is an extremely generous and capable person whose only fault may be that his unbounded enthusiasm and inability to squeeze more than twenty four hours out of a day have left too little of himself to go around. Oli de Weck was always a great source of encouragement and an excellent subject matter expert. Dan Whitney gave generously of his time and was actively involved in the final writing process for my dissertation. His criticism was tough, but objective. Dan pushed me to be a better writer and deserves credit for many of the positive aspects of this document.

I owe a huge debt of gratitude to the companies and employees that participated in this research. Only one program, Lockheed Martin's F-35 program, was publicly acknowledged. (A tri-variant fighter aircraft program is nearly impossible to disguise.) I would like to thank Tom Burbage for his executive support of the F-35 study. Without his support, the study would have been nothing more than a proposal. In addition, I would like to thank Paul Labar who gave me a tremendous amount of support and who ultimately enabled the F-35 case study to be as successful as it was. I would also like to thank the many F-35 team members who did their best to help me to better understand a truly amazing aircraft program. The other six case study companies remain disguised. Individual participants cannot be named, but their help is deeply appreciated. The opportunity to spend time within these companies was invaluable from a research perspective and from the standpoint of my own professional interests. To each of the companies, executive sponsors, case study contacts, and interview participants: THANK YOU!

Many additional individuals provided guidance and help at various points in the PhD process. I would particularly like to recognize Ernst Fricke, Earll Murman, Eric Rebentisch, Donna Rhodes, and Warren Seering. They have willingly given their advice and it was greatly appreciated. Additionally, Kathi Cofield helped me immensely by ensuring that I always had meeting time with Ed. Kathi was a great friend and supporter throughout this process.

Last but not least, I need to thank my fellow graduate students for their support, encouragement, and research insights. While the list is long, I would especially like to thank Luca Bertuccelli, Gergana Bounova, Bruce Cameron, Joao Castro, Heidi Davidz, Ralph Hall, Mike Hanowsky, Wilfried Hofstetter, SeungBum Hong, Ben Koo, Jijun Lin, Dave Long, Pedzi Makumbe, Jim McFarland, Sid Rupani, Bill Simmons, Eun Suk Suh, and Christine Taylor.

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1. Introduction

Product development is a complex undertaking that involves a near countless number of decisions, each of which may impact revenue and cost and ultimately, a product's contribution to corporate profitability. Various strategies and tools exist for increasing revenue and decreasing lifecycle cost. For example, revenues may be increased by optimization of a product design for a given market segment and through offering increased numbers of products in the marketplace. Fixed costs of development may be lowered through improved development methods and tools, such as the use of Computer Aided Engineering software. Variable costs of production may be controlled through Design for "X" strategies such as Design for Assembly and Design for Test. Development strategies and tools such as these all have merits but must be carefully considered in the context of their impact on overall profitability. Focusing too heavily on any one strategy or tool, may produce negative results for the product family as a whole.

Commonality, or the reuse and sharing of assets such as components, processes, technologies, interfaces, and/or infrastructure, across a product family[1], represents one of the many potential strategies for improving corporate profitability. Through reuse and sharing, a company may be able to more efficiently develop, produce, and support its products; i.e., produce products with higher lifecycle profits, reduced average lead times, and reduced risks. Total lifecycle costs may potentially be reduced for product families that are based on commonality due to potentially reduced development scope, shared economies of scale, and increased degrees of learning, to name a few examples. Revenues may increase when commonality enables a company to produce greater numbers of competitive products, while revenues may decrease when commonality causes a loss of product differentiation and/or market competitiveness. A popular example of the former is the often-cited case of the Sony Walkman (Sanderson & Uzumeri, 1995). The extent to which benefits are realized from pursuing commonality depends on a complex array of factors that includes market conditions; product differentiation; product designs and their degree of commonality; relative production volumes; product timing; and management practices. Determination of the degree of commonality within a product family represents one of many challenging trades associated with product development.

Commonality results from reuse of assets that were previously developed to meet the needs of another product (reuse of "Intended Unique") and, in some cases, from reuse of assets that were specifically developed to meet the needs of multiple products (reuse of "Intended

[1] Meyer & Utterback define a product family to be the "products that share a common platform but have specific features and functionality required by different sets of customers" (Meyer & Utterback, 1993, p. 30). In this dissertation, the definition is less focused on an underlying platform and more focused on sets of market needs and a company's decision to group products together; i.e., product design commonality is not a requirement. In this dissertation, the "platform" represents common assets such as those listed in the definition of commonality.

Common"). Two development methods support the creation of these potentially common assets: "independent development" and "platform-based development." Both are described briefly below.

The default approach to the development of product family members, referred to in this dissertation as "independent development," entails the application of a product development process that aims to efficiently create an individual product family member that is targeted to a specific set of market needs. The outputs of this process represent "Intended Unique" assets that were developed solely for the purposes of one product. During the development process, development costs, lead times, and risks may be lowered by reusing previously developed Intended Unique assets. In this case, Intended Unique assets actually become common to two or more products. In a rational decision making environment, these pre-existing assets would be screened for fit with the requirements of the current program and new development would only be undertaken when required to bridge the gap between the current set of requirements and the capabilities of the pre-existing assets. Independent development with reuse of Intended Unique assets is a natural approach to development and is prevalent in practice. While certainly effective from an individual product perspective, the approach may be inefficient from the perspective of overall corporate profitability: potential synergies between future products and/or other products currently in development are neither evaluated nor exploited when determined to be beneficial.

Through the development and utilization of Intended Common assets, "platform-based development," offers an expanded set of options with respect to commonality. New product designs are created through new Intended Unique development; new Intended Common development; reuse of previously developed Intended Unique assets; and reuse of previously developed Intended Common assets (if present). The core expectation of platform-based development is that the development and reuse of Intended Common assets increases the net benefits of commonality over and above the benefits that could be achieved through the development and reuse of Intended Unique assets, or through no reuse at all. As in the case of reuse of Intended Unique assets, a proactive approach to enabling commonality is only a means to an end: through exploiting potential synergies across products, the firm aims to improve its overall profitability. A proactive approach to enabling commonality is advantageous to the extent that the approach contributes to the ultimate profitability goal, or to the extent that it decreases net costs in the case of non-profit organizations that do not have revenues.

Examples of platform-based development approaches are widespread in industrial practice. Commercial aircraft such as the Boeing 777 are often designed around a strategy of commonality (Sabbaugh, 1996). Cockpit commonality and the associated operations benefits have been embraced by multiple aircraft manufacturers and their customers. According to Airbus, the A380 "uses the same cockpit layout and operating procedures as the Airbus A320 and A330/A340 Families, ensuring that pilots qualified on other Airbus fly-by-wire aircraft can step into the A380 with minimal additional training" (Airbus). Customer operating costs are reduced as a result. The auto industry has pursued commonality since the time of Henry Ford[2].

[2] For examples of Ford's interest in commonality, which he referred to as "standardization," see Ford (1926).

Volkswagen's A platform of the late 1990's is a more recent example, having been shared across the Golf, Jetta, New Beetle, Audi TT, Audi A3, Skoda, and Seat (Bremner, 1999). Volkswagen's C platform was used to support the VW Passat, Audi A4, Audi A6, and Skoda Superb (Csere, 2003). Nissan shares its D platform between multiple vehicles, including the Murano SUV and Altima coupe (Stewart, 2008). Even consumer products have heavily leveraged commonality, with the Sony Walkman being a popular example (Sanderson & Uzumeri, 1995). Sony utilized product platforms and flexible manufacturing investments to lower its design and manufacturing costs. As a result, Sony was able to introduce a greater number of products than its competitors, enabling increased numbers of market "tests" to be performed and an overall increase in revenues. Black & Decker's 1970's platform-based redesign of its electric hand tools around standard parts and interfaces represents a second consumer product example. The Black & Decker product family was extremely successful in reducing production costs and implicitly, product development costs, with much of the competition being unable to match Black & Decker's prices (Meyer & Lehnerd, 1997).

Success is not a given for platform-based product families. Lack of product differentiation may result as was the case with General Motors' experience with commonality in the 1980's: commonality was taken too far and General Motors was criticized for a lack of differentiation between product models. The 1983 Fortune magazine cover photo of four nearly identical maroon automobiles from Chevrolet, Oldsmobile, Buick, and Pontiac (Burck, 1983) was likely a significant embarrassment for the company. Volkswagen experienced similar challenges with what was perceived by some to be a lack of differentiation between its Volkswagen and Skoda products; a lack of differentiation that likely resulted in cannibalization of higher-end auto sales in light of lower cost alternatives ("Ford's Nemesis," 2000; "Problems with the People's Car, Volkswagen," 2002). Volkswagen also had problems when it attempted to base the Audi TT on its A4 platform: aerodynamic lift at the rear of the car created handling issues that required suspension changes and the addition of a rear spoiler (Ruff, 2000). Toyota, a company known for high quality, has experienced increasing numbers of recalls, an issue that has been blamed in part on the fact that common parts are being utilized across more vehicle models (Shirouzu, 2006). A rich defense industry example of a failed attempt at commonality comes from the "Tactical Fighter, Experimental" (TFX) program of the 1960's that ultimately became the F-111 fighter aircraft. The aircraft program was intended to provide the United States Air Force (USAF) and Navy with a common aircraft that could meet the needs of each service branch in a cost effective manner. As the program progressed, the contractors struggled to maintain commonality while meeting performance requirements. The ultimate outcome of the TFX program was the cancellation of the Navy variant after having invested $400 million (FY1969) in that variant and after repeated attempts to create an acceptable USAF version. While the lost $400 million (FY1969) investment was significant, the resulting compromises in the United States Air Force variant were likely orders of magnitude more costly in terms of lost performance and increased unit cost.[3]

Factors such as strong industrial interest in commonality; the potential impact of commonality on the corporate bottom line; and mixed industrial success have led to significant academic

[3] This section is based on Art (1968) and Boas & Crawley (2007).

research on the topic of commonality, both in the management and engineering domains. Underemphasized in the academic literature (which is reviewed in Chapter 2) is a clear discussion of the benefits and penalties of commonality, a topic that forms the basis for the proper evaluation of commonality opportunities and that serves as the central topic of this thesis. To date, the benefits and penalties topic appears to have been mostly addressed by way of motivating the need for a new design method or tool; as an introduction to the analysis of a specific application; or as a part of a general managerial discussion. Additionally, the benefits of commonality appear to be emphasized more than the penalties. Beyond an apparent under emphasis of the benefits and penalties topic, there seem to be two critical opportunities for improving the connection between academic understanding and the realities of industrial practice, especially in the domain of complex products.

The first opportunity relates to the implicit expectation that commonality is implemented as planned. The reality is that the pursuit of commonality requires the consideration of the phenomenon of "divergence," or the tendency for commonality to decrease with time. Divergence may be beneficial or non-beneficial from the standpoint of product family profitability but always creates a reducing effect with respect to the planned benefits of commonality. Failure to account for beneficial divergence may cause companies to resist divergence and to negatively impact their profitability as a result. Failure to account for non-beneficial divergence has two potentially negative impacts on corporate profitability. First, overoptimistic estimates of the benefits of commonality are likely to be produced during the product family planning and preliminary design phases. This over-optimism may lead to the pursuit of Intended Common elements that ultimately create penalties with respect to the alternative of independent development. Second, failure to account for non-beneficial divergence may lead companies into complacency with respect to managing commonality throughout the lifecycle of the product family with the result being the non-beneficial loss of commonality. In this case, penalties were incurred to produce Intended Common elements, yet benefits were not realized due to divergence. Divergence has implications for both upfront program planning and lifecycle management of commonality. A focused description of divergence and guidance on its management were not identified during the literature review.

The second opportunity is the fact that while much of the existing literature assumes, either explicitly or implicitly, that all product family members are developed in parallel, this is rarely the case in complex product families. The members of a complex product family are typically developed in a sequential, rather than parallel, manner. The temporal separation between products is referred to as "lifecycle offset" in this dissertation. As is demonstrated in this dissertation, lifecycle offsets tend to reduce the value of commonality. For example, lifecycle offsets make development of common designs more challenging due to increased future uncertainties and a lack of coordination between current and future product development programs. Applying a parallel development assumption to estimates of commonality within sequentially developed products may, once again, produce overly-optimistic predictions of the benefits of commonality. As with divergence, a focused description of lifecycle offsets was not identified during the literature review.

Based on the literature review, divergence and lifecycle offsets represent key research topics that are believed to be important to improving industrial practice and that require further research. The objective of the research described in this dissertation was to better understand divergence and lifecycle offsets as they relate to the economic benefits and penalties of commonality in the context of complex product families. The economic benefits and penalties topic is strongly influenced by managerial actions. The key research questions addressed within this dissertation are:

1) *What are the economic benefits and penalties of commonality in the context of divergence and lifecycle offsets?*

2) *What are the managerial implications of divergence and lifecycle offsets?*

Addressing the research questions is important for both the academic research community and industrial practice. Both groups require an improved understanding of the economic benefits and penalties of commonality in order to properly evaluate opportunities for commonality. As will be discussed later, industry appears to struggle with the proper evaluation of commonality opportunities and the literature appears to assume an economic benefit. Addressing the management implications question is obviously geared more toward industrial practice than academia: addressing this question is important for linking research insights to the advancement of industrial practice.

The methodology utilized to investigate the research questions combined literature review; case study research; and the creation of a simple cost model of commonality. The literature review was utilized to create initial hypotheses about divergence and lifecycle offsets. Case study research was then conducted to provide a general investigation of commonality within the context of complex product families and a specific investigation into divergence and lifecycle offsets. The seven case studies examined products in the aerospace, automotive, and high tech sectors and provided a window into the realities of industrial practice with respect to commonality. Each case entailed the buildup of the product family history from the perspective of commonality; the identification and description of factors that influenced the overall benefits and penalties of commonality; and the examination of both formal and informal management actions that influenced commonality. The case studies led to significant refinements of the initial hypotheses and to an improved understanding of the economic value of commonality. Valuable insights were also gained into the general state of practice with respect to the management of commonality. The simple cost model helped to explain several of the key case study findings in a more analytical manner than could have been achieved with prose alone.

Several limitations of this work must be mentioned. The first is the fact that the research primarily takes an economic perspective in examining the benefits and penalties of commonality. Other important, high level concerns such as product lead time and risks are assumed to be expressible in economic terms. For example, the risk of component failure in fielded products can be viewed as a probability weighted cost. The second limitation is the primary focus of this research on cost, rather than profitability. This research assumes that cost reduction is the primary *potential* benefit of commonality. Through implementation of commonality, development and production costs may decrease. A company may choose to utilize these savings in a number of ways including recognition of increased profit margins and investment in the development of additional products (which should also lead to increased profits). The latter outcome could be viewed as a benefit of commonality, but this research assumes the outcome is the result of a decision to reinvest the savings created by commonality; i.e., additional products could be developed with the savings that result from implementation of any strategy or tool that creates cost savings. The third limitation of this research is one of lifecycle scope: this research has focused primarily on the development and production phases of the product family lifecycle. This focus reflects the main focus of the companies that participated in the case studies and a decision to exclude customer interactions (which would have driven increased operational emphasis). Fourth, while the findings of the seven cases appear to have applicability to the development of many types of complex product families, the case findings ultimately only describe the seven cases. Broader applicability can only be proven through further investigation. Lastly, it is important to state that while this dissertation makes what is believed to be a strong contribution to the benefits and penalties discussion, the research by no means provides the "final answer." The complexity of the benefits and penalties discussion presents a fruitful avenue for significant future research that could have broad implications for both industry and academia.

The remainder of this document is organized as follows. Chapter 2 presents several descriptive frameworks that are utilized throughout this dissertation and a review of the existing literature as it relates to the economic benefits and penalties of commonality, divergence, and lifecycle offsets. Chapter 3 discusses the field research methods utilized for the case studies and also discusses an automated tool that was developed to analyze commonality within product families. Chapter 4 presents the seven case studies and their outputs; provides two of the summary reports in full; and discusses relevant cross-case findings. Chapters 5 and 6 provide deeper descriptions of divergence and lifecycle offsets, leveraging the seven case studies for insights and examples. Chapter 6 also utilizes a simple mathematical model to illustrate the cost benefits and penalties of developing Intended Common components in comparison to the alternative of developing Intended Unique components, all within the context of divergence and lifecycle offsets. Chapter 7 concludes with a brief summary of the findings of this research; recommendations for improving industrial practice; and potential avenues for future research.

2. Proposed Commonality Frameworks and Review of Relevant Literature

This chapter presents several conceptual frameworks that are utilized throughout this dissertation, followed by a discussion of the relevant academic literature, and a summary of factors that influence the cost benefits and penalties of commonality as identified in the literature. Frameworks are presented for lifecycle offsets and for the classification of commonality. The literature review then examines three bodies of literature: the general management literature on product families and product platforms; quantitative management models of commonality; and the engineering literature on the design and optimization of platform-based product families.

2.1. Proposed Commonality Frameworks

2.1.1. Lifecycle Offsets

Product families consist of individual members or variants that may or may not have been developed and released at the same time. The concept of a product family map (e.g., Robertson and Ulrich, 1998) provides a high level view of the product family's history. Figure 1 illustrates a generic product family map that begins with the introduction of Product A, followed by the introduction of Product B into a new market segment; followed by Product C into a third market segment. Product D then replaces Product A in the original market segment and Product E replaces Product C. Lines on the chart indicate heritage. For example, Product D may benefit from the reuse of certain components, processes, and technologies from Product A and Product B. Differences in product introduction timing have been recognized by many researchers with examples including Robertson & Ulrich (1998); Cusumano & Nobeoka (1998); Maier & Fadel (2001); Umeda et al. (1999); and to some extent, Uzumeri & Sanderson (1995).

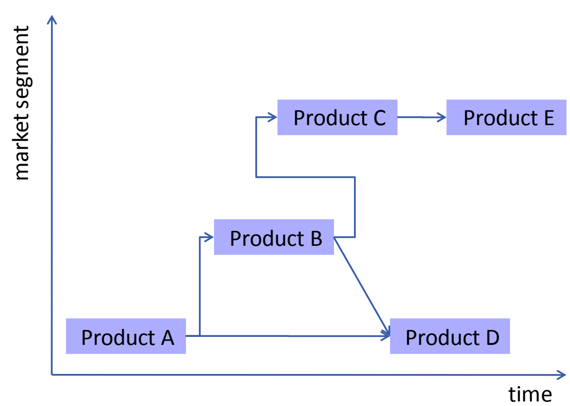

Figure 1: A product family map illustrating new product introduction (Products A, B, and C) and replacement (Product D replaces Product A and Product E replaces Product C). Arrows indicate potential heritage.

Each of the individual products in a product family follows an individual product lifecycle that consists of phases such as planning, development, production, operations, and retirement (Figure 2).[4] The lifecycle phases are not necessarily serial as illustrated in Figure 2. For example, significant overlap typically exists between the production and operations phases when considered from the perspective of a given product.[5] Figure 2 illustrates the start order of the phases rather than a completely serial execution of each phase.

Figure 2: A typical product lifecycle.

The combination of the high level product family map (Figure 1) with the individual product lifecycle (Figure 2) provides a critical framework for discussing the benefits and penalties of commonality in the context of potential lifecycle offsets. Figure 3 illustrates a family of two products that are derived from a common product family planning process and are assumed to have some degree of commonality. An offset exists between the start of Product A development and the start of Product B development. For the purposes of simplification, this dissertation assumes that each phase length is equivalent for all products and that the relationship between production and operations is constant for all products. These assumptions allow one parameter, “offset,” to describe the temporal relationships between all phases. The assumptions allow for clearer communication of the key points made in this dissertation but the assumptions must be eliminated in order to allow future extensions to this research that could directly address the lead time implications of commonality.

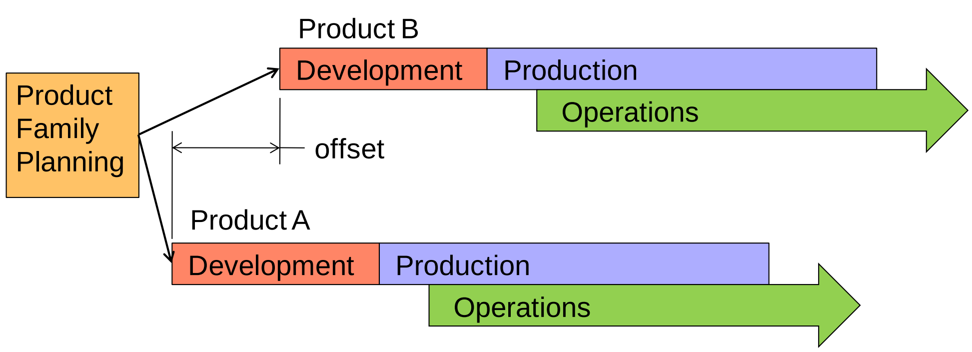

Figure 3: Two-product family with offset lifecycles. (Retirement phase not illustrated.)

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[4] See Ulrich & Eppinger (2000) and Pahl & Beitz (1996) for additional lifecycle examples and discussion.

[5] It is important to keep in mind the difference between a product and an individual instance of a product. “The product” is a design that is developed; produced and sold multiple times; and then operated and serviced. An individual instance of a product is manufactured, uniquely identified by a serial number, and sold to a specific customer who then operates the product. While overlap may occur between phases of the product lifecycle, an individual product instance typically undergoes production, operations, and retirement phases in a serial manner.

The degree of offset between any lifecycle phase type (e.g., between the development Phases of Product A and Product B) can vary from none (completely parallel lifecycles) to very large (no overlap). Of interest in this dissertation are the degrees of overlap in development and production. Three general cases are illustrated in Figure 4. The illustrations refer to development offsets although the same terms may be applied to the production phase. "Parallel" refers to the execution of the same lifecycle phase of two or more programs at the same time. "Sequential Non-Overlapping" refers to the serial execution of lifecycle phases for different products. "Sequential Overlapping" refers to partially overlapping product lifecycle phases and represents the general case. Offsets and differences in overlap, or the time during which both products are in a given lifecycle phase, modify the benefits and penalties of commonality as discussed later in this dissertation.

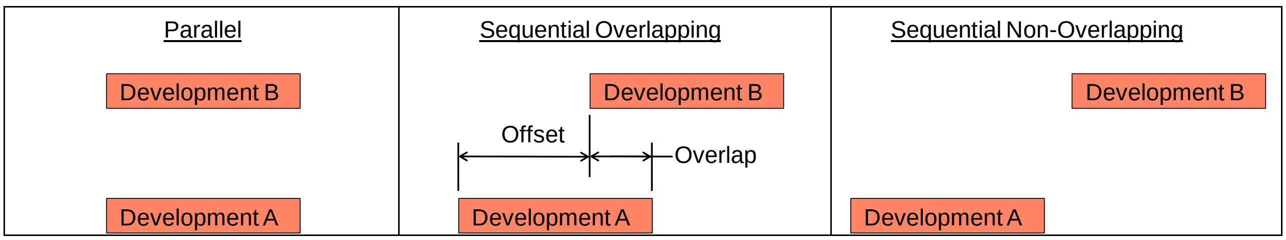


Figure 4: Parallel, Sequential Overlapping, and Sequential Non-Overlapping lifecycle phases. The development phase is shown, although the same concept applies to all lifecycle phases and has implications for the benefits and penalties of commonality.

2.1.2. Classifying Commonality

It is useful to classify types of commonality in order to be more precise in later discussing the benefits and penalties of commonality. The discussion here and in much of the remainder of this dissertation focuses on common components (e.g., the subassemblies and individual parts of a given product). It is important to recognize that, in the context of complex products, subassemblies often contain both hardware and software elements.[6] The concept of common components is believed to be the most easily understood, although the classification is equally applicable to process. Analogies can also be made for more abstract concepts such as technology commonality.

Any two components may be classified as common, similar, or unique.[7] "Common" represents the most well-defined of these three terms. A common component is fit, form, and function identical; typically having the exact same part number. "Unique" represents the other end of the spectrum, although this end is somewhat arbitrary. In terms of this dissertation, unique means that the existence of one design has little effect on the cost structure associated with the second. Unique components have different part numbers. In between the common and unique ends of the spectrum are "similar" (also referred to as "cousin") components, meaning

[6] This dissertation research has a heavy bias towards physical components of complex products. At the subassembly level, these components often include software, although software reuse was not specifically addressed as part of this research.

[7] Others have recognized this three-way classification of the degree of commonality. For example, see Fujita et al. (1998).

that similar components represent a very broad range from almost common to almost unique (Figure 5). Definitions such as “development of a similar part requires less than 40% of the original development investment” help to narrow the scope, but the scope is still broad.

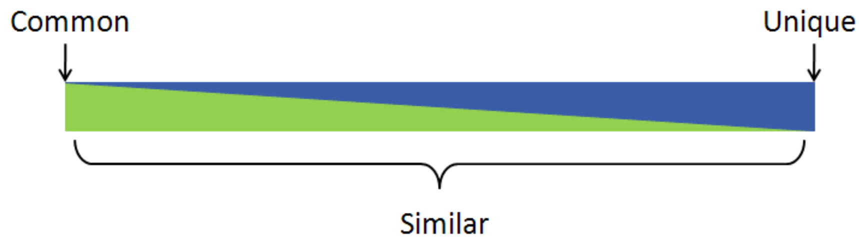


Figure 5: The spectrum between "common" and "unique." “Similar” (“cousin”) represents a broad range of potential commonality levels.

This research avoids the ambiguity associated with similarity whenever possible by taking the following perspective: similarity is interpreted as the existence of both commonality and uniqueness at lower levels than the current reference frame. In other words, similarity requires further design decomposition to identify common and unique components or component attributes. For example, if a similar engine is shared between two vehicles, analysis of components at a lower level may identify both common and unique components. The engine may consist of common components with the exception of unique air intake and fuel injection components. The same argument can be taken to the level of individual parts that are similar. In this case, the parts share common and unique attributes. As an extremely simple example, consider two rods of the same diameter and material type but different length. The rods have the common attributes of diameter and material type but a unique length. As an additional example on a much more complex scale, commercial aircraft fuselages share a common diameter within a given family of models, with length, a high level attribute, being scaled to address different passenger capacities. Although every part could be different in the two fuselage sections (unlikely), the sections share a common attribute that enables common tooling and common or similar manufacturing processes (Whitney, 2004, p. 351).

While the common-similar-unique classification provides an indication of the degree of realized commonality, a discussion of the benefits and penalties of commonality must also consider how this level of commonality was arrived at. At the highest level, components utilized for a given product may either be reused from prior programs or newly developed. In the case of reuse, a component may be utilized as-is (“Direct Carryover”) or it may be altered in some manner to meet the needs of the new program (“Modification”). In the case of new development, components may be developed with the intent of being utilized solely in connection with one product (“Intended Unique”); developed with the intent of being modified in a pre-defined manner to meet the needs of more than one product (“Intended Similar”); or developed with the intent of being shared between more than one product (“Intended Common”). Whenever possible, the Modification and Intended Similar categories are avoided in this dissertation due to the ambiguity discussed in the previous paragraph. Refer to Figure 6 for a classification tree. The fact that new components are decomposed into three categories that all start with the word "intended" is important for understanding the benefits and penalties of commonality, as is discussed further below.

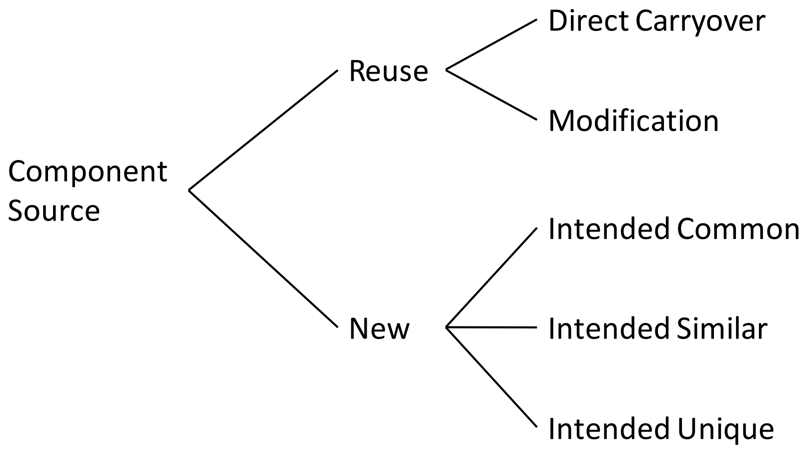


Figure 6: A classification for component sources in new product development programs.

A simplified version of the relationships that ignores Similarity and Modification is illustrated in Figure 7 for the case of two sequentially developed products. This framework is used throughout this thesis to discuss the implications of design intent at the time of Program A and actual outcomes at the time of the later program, Program B. The framework assumes that Product A is developed at Time 1 with both Intended Common ("IC") and Intended Unique ("IU") components. At Time 2, Product B is developed. At that time, the Intended Common and Intended Unique components become either Common to A and B or Unique to A. No change has occurred to the design of these components, only their status. The status change is based on whether or not the components are selected for incorporation into Product B. In addition, new unique components ("Unique B") may be created at Time 2.[8] The five classes of components are summarized below:

- **Class 1: Intended Product A Unique Components that Actually are Product A Unique ($IU_A \rightarrow U_A$).** These components are developed without the intent of reuse in Product B and are not utilized in the Product B design.
- **Class 2: Intended Common Components that Become Product A Unique ($IC \rightarrow U_A$).** Components in this class were intended to be common to both products, but in the end, are not utilized in the Product B design.
- **Class 3: Intended Product A Unique Components that Become Common ($IU_A \rightarrow C$).** These components were developed during Program A with the intent of only being

[8] The two product framework presented here is the simplest framework that could be utilized to examine changes in planned/actual commonality over time. The framework could be extended in many directions, a few of which are listed here. First, reuse may occur at Time 1. Second, reuse may come from multiple sources, not a single product as suggested in this simple framework. Third, Intended Common development may occur at Time 2, with the intent being the support of future products. Fourth, more than two products may be considered. Fifth, retrofits of earlier products may be considered.

utilized by Product A. A decision is made at Time 2 to incorporate these components into Product B.

- **Class 4: Intended Common Components that Actually Become Common (IC→C).** This class of components represents components that were developed for use in Products A and B and that are actually utilized in both of these products.
- **Class 5: Intended Product B Unique (U_B).** These components are developed as part of the Product B development effort. In the sequential, two-product model presented here, this component class is unique by definition.

Within this dissertation, the five component classes represent the superset of components that make up Product A and Product B.[9] The design of Product A consists of the components in Classes 1 through 4. The design of Product B consists of the components in Classes 3 through 5. Each class is assumed to represent the aggregate collection of all components within that class.

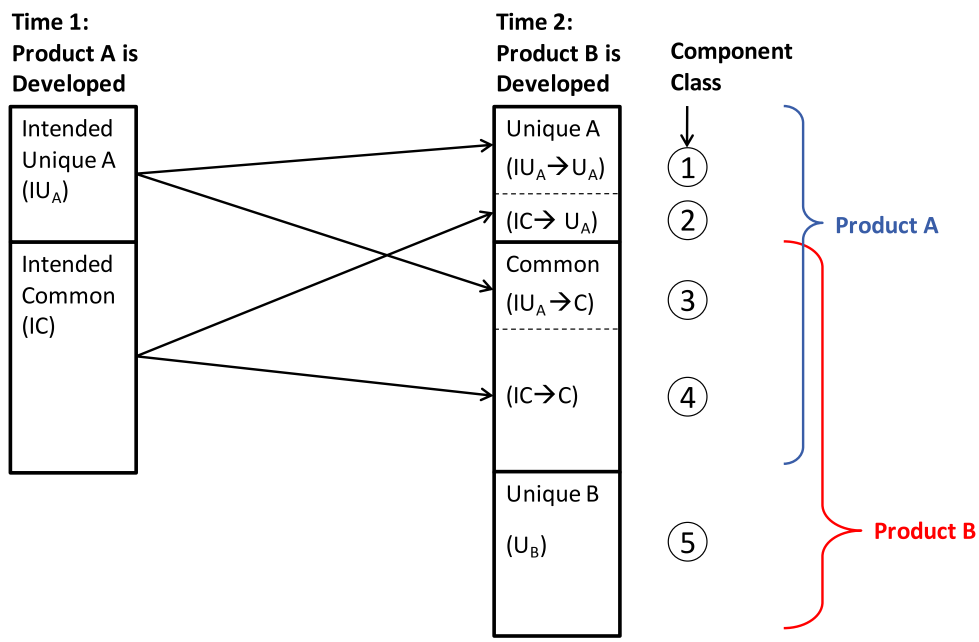


Figure 7: A two product family can be classified into five component classes that are based on design intent (left) and actual product design outcomes (right). The left and right columns represent the superset of components available at Time 1 and Time 2, respectively. The circles indicate the five classification designations used in this dissertation. Product A consists of Classes 1 through 4. Product B consists of Classes 3 through 5.

A reference point for the development scope (cost) of each component classification is delineated in Figure 8. A product family starts as a vision that includes a certain degree of Intended Common components, $COMM$, and Intended Unique components, $1 - COMM$. These fractions are multiplied by the cost of developing an independent version of Product A, $C_{dev,ind.,A}$, to create a development cost reference for common and unique components, *as referenced to the cost of the independent alternative*. Discounts and penalties may be added to

[9] The reader is reminded that while the focus here is on product components, analogies can be drawn to other types of commonality, such as potential commonality in manufacturing processes.

each estimate to account for the benefits and penalties of commonality. During development of Product B, the potential reuse of Intended Unique components,$Reuse_{IU}$, the potential loss of Intended Common components, Div, and the total scope of Program B, $C_{dev,ind.,B}$, combine to form the five classes. Product B unique cost (scope) is defined by subtracting the reuse of Intended Unique component values (Class 3) and reuse of Intended Common (Class 4) component values from the cost of developing an independent version of Product B, $C_{dev,ind.,B}$.

The five classifications described above, along with the equations of Figure 8 are utilized throughout this thesis in discussions of both development and production costs. Production costs are assumed to be related to development costs through a simple ratio. This simplifying assumption could be relaxed in future work. The equations of Figure 8 are essential to the simple cost model that is described in Chapter 6.

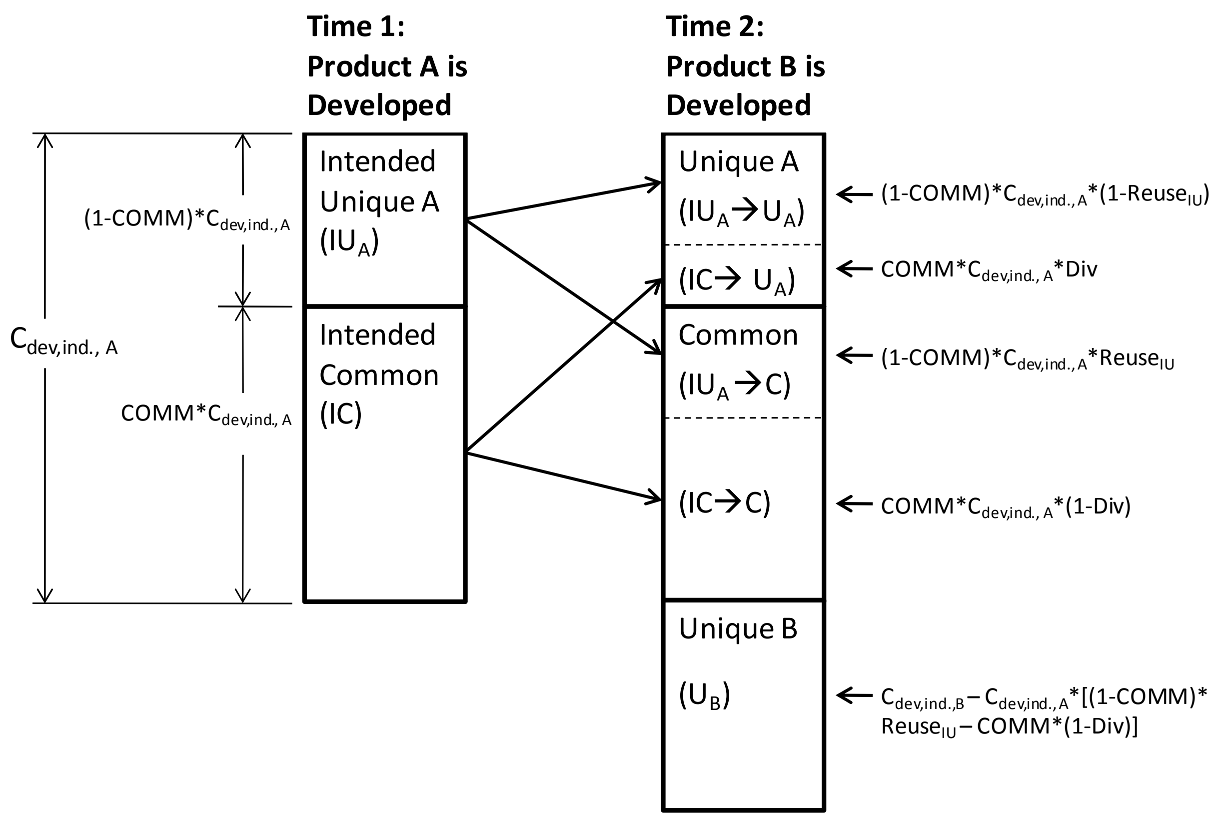


Figure 8: The five component classifications with equations that define development cost references for each component class. Benefits and penalties of commonality must be applied to these reference points. Within this dissertation, production costs are assumed to be related to these references. Refer to Chapter 6.

2.2. The Literature on Commonality

A literature review was utilized to gain insights into the general topic of the benefits and penalties of commonality. The examination of the literature also contributed to the formation of two hypotheses that seemed to be important in the context of complex product families. The first hypothesis was that lifecycle offsets are common in complex products and that these offsets have a significant impact on the benefits and penalties of commonality and on industrial approaches to commonality in general. The second hypothesis was that commonality tends to reduce with time (i.e., that divergence occurs) and that this reduction in commonality has negative impacts on product family profitability. As will be discussed later, the initial divergence hypothesis was erroneous and was significantly refined during this research.

For the purposes of this research, the existing literature was classified into three categories: the general management literature on product families and product platforms; quantitative management models of commonality; and the engineering literature on the design and optimization of platform-based product families. The categorization is inexact, but does provide some useful structure.

2.2.1. The General Management Literature on Product Families and Product Platforms

The general management literature provides an excellent, high-level overview of commonality concepts, mostly under the topics of product platforms and product families. The message is consistent: platforms and commonality will improve overall corporate profitability. The management articles tend to focus on product family planning, with some discussion of the organizational structures and management practices that aid and hinder attempts to exploit commonality.

<u>The Power of Product Platforms</u> (Meyer & Lehnerd, 1997) provides guidance for the creation of platform-based product family strategies; guidance that is targeted at a senior management audience. Meyer and Lehnerd argue that a company's long term success relies on streams of successful products and that these streams of products are best created through platform approaches rather than through the repeated development of independent products. Established platforms enable companies to respond to future market opportunities and uncertainties through the rapid introduction of new models and through an improved focus on advancing core technologies and capabilities that can be leveraged across many products.

The book's examples of successful implementations are primarily based on consumer products, including the widely cited 1970's Black & Decker hand tool redesign that was undertaken in response to a regulatory requirement for double insulation. The most notable output was a motor design that maintained a common motor diameter across the product family members, with length being increased or decreased in order to change power output. The length scaling approach allowed for common manufacturing equipment and provided a significant reduction in manufacturing costs. In addition, components such as switches, cords, and fasteners were standardized to provide economies of scale.

Meyer and Lehnerd cite several of the potential benefits and penalties of product platforms throughout their book, although they do not provide guidance on evaluating these benefits and penalties in relation to the alternative of independent development: platform-based development is approached as the proper approach to development. Examples of cited benefits of product platforms include an increased new product model introduction rate; decreased derivative development cost; and realization of economies of scale in manufacturing. Recognized penalties include increased development expense for the actual platform and the potential for a platform flaw to impact multiple products. Detailed descriptions of these benefits and penalties, along with their trades are not provided.

In a summary article, Meyer (1997) provides additional discussion of the benefits and penalties of platforms, in the context of a management article that strongly advocates for platform-based approaches to product development. Claimed benefits are dramatically reduced manufacturing investments in support of new products; economies of scale in part procurement; and fast integration of new components (reduced R&D time) as new market opportunities are identified. A stated penalty of commonality is the potentially greater negative impact of a flawed common component in relation a unique component. Additionally, Meyer recognizes the potential negative profitability impact that may arise through the use of higher capability components in lower-end market segments, increasing a product's underlying cost in a way that is not offset by increased revenues. In this dissertation, the cost associated with utilizing components with excess capability is referred to as the "cost of excess capability" or a "capability penalty."

The paper by Meyer and Utterback (1993) is similar to the discussion of the previous two documents authored by Meyer but is more focused on the dynamic nature of an underlying product platform and on the broader picture of a firm's evolving capabilities. The authors define the platform as the design and components shared by a set of products, but push for a much broader view of the product family "core" that includes the common product platform, common user needs, common distribution channels, and common manufacturing processes. The core represents key organizational capabilities that last longer than product families and their individual products. By pursuing platform-based approaches, companies are able to eliminate redundant technical and marketing effort associated with independent product development. The ability to simultaneously introduce multiple products rather than to release single, independently developed products is listed as a benefit. The authors recognize the tradeoff between development of the platform and the potential for rapid development of new products based on this platform.

Robertson & Ulrich (1998) present an additional approach to platform planning. In their definition, a platform consists of "the collection of assets that are shared by a set of products." These assets are classified as components, processes, knowledge, and people and relationships. Robertson & Ulrich provide more structured guidance on the implementation of platform-based development than that of Meyer & Lehnerd. They call for the explicit analysis of commonality and distinctiveness, with relationships between the two being determined by a given product architecture. Increasing distinctiveness is linked to increasing revenue, while decreasing distinctiveness and increasing commonality both lead to reduced costs. Properly managing this trade increases profitability. Their specific approach to managing this trade utilizes a product plan (contains products and timing of their releases), differentiation plan (addresses differentiating attributes for each market niche), and commonality plan (economic analysis that accounts for commonality). Their approach explicitly calls for economic analysis, providing a basis for making decisions about what components should be included in the platform versus remain unique to a given product. The authors present the example of an automotive instrument panel that utilizes common and unique components and realizes development and manufacturing cost savings as a result.

Robertson & Ulrich explicitly discuss the benefits and penalties of platforms. They sum up their high-level view of the benefits as follows:

> *"By sharing components and production processes across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing processes, and take market share away from competitors that develop one product at a time." (Robertson & Ulrich, 1998, p. 20)*

Other benefits listed in the paper are as follows. Platform-based products are more easily tailored to market needs due to the reduced incremental cost and lead time of follow-on model development in comparison to independent programs. These development improvements result from reduced development scope (e.g., reductions in design and test workload for new parts and processes). Manufacturing cost is claimed to be lower due to shared economies of scale benefits associated with common part production rates, although consideration of the tradeoff between this benefit and the potential for a capability penalty appears to be missing. Investments in production infrastructure are reduced through the sharing of production equipment, although the implicit assumption here is that the capacity limits of the existing production system are not exceeded by the aggregate demands of common components. Commonality also reduces complexity costs that impact operational areas such as materials management, logistics, sales, and service. Risk reduction results due to the lesser development scope associated with each product derived from the platform.

Robertson & Ulrich list the potential penalties associated with platforms as including an increased development complexity that is associated with initial platform definition; costs of additional coordination; and typical organizational unfamiliarity with the platform development process. Additionally, the potential cost benefits of commonality must be balanced against the market need for distinctive products; i.e., commonality may reduce revenue.

Missing in the article is a discussion of the potential cost, lead time, and risk implications of developing the initial platform. The statements about the benefits of platform-based development assume the existence of a platform and do not address the penalties of development.

A lifecycle offset between the development of two products is explicitly recognized (e.g., "The Product Plan"), although this difference is presented as a matter of choice:

> *"Some companies choose to issue several products simultaneously; others choose to launch products in succession." (Robertson & Ulrich, 1998, p. 24)*

The commonality plan and its associated cost information are built upon the product timing ("offsets") defined by the product plan and the authors recognize that changes in product timing will change the relative manufacturing investments. Little additional guidance is provided with respect to the influence of product timing (lifecycle offsets) on the relative benefits and penalties of commonality, except that changes in product sequencing may change the relative incremental costs associated with later derivatives. Building out a clearer understanding of lifecycle offsets represents a significant opportunity that is at least partially addressed by this dissertation.

Through an examination of “Design for Changeability,” Fricke and Schulz (2005) emphasize the need to create product architectures that allow for continuous product evolution; either the evolution of an underlying design or the evolution of actual, fielded products. Their article highlights changes created by the passage of time; i.e., with lifecycle offsets. The authors recognize the prevalence of change due to marketplace dynamics, technological evolution, and environmental variety and state that product architectures must be designed either to adapt to these changes or to be robust to them. Design for Changeability is focused on addressing both foreseen and unforeseen changes within the system lifecycle. Within this framework, platform-based development is presented as an approach that pursues mostly pre-planned product variants; i.e., Design for Changeability is broader in scope than platform-based development.

Along a similar line of research, Rothwell & Gardiner propose the creation of “robust designs” as a method for addressing future product uncertainty. Robust designs are “a special type of design capable of evolving into a design family of variants which meet a variety of changing market requirements" (Rothwell & Gardiner, 1988, p. 373). These designs “contain the basis for not just a single product but rather a whole product family of uprated or derated variants” (Rothwell & Gardiner, 1990, p. 283). Robust designs are implied to be more easily changed than the alternative of “lean designs” which are developed with a set of immediate needs in mind. In effect, the authors are making the case that creating Intended Common elements (i.e., platform-based development) is more effective than the alternative of multiple, independent development efforts.

The presented robust design examples are based on sequential development of complex products and are all successful programs. The examples include aircraft engines, cars, copiers, and hovercraft. The Rolls-Royce aircraft engine example provides insights into the evolution of product models. The RB211 family started with a base model, the 22B. The front fan module was later replaced to produce a derated thrust engine, the 535C, with the original 22B model being retained. Later, a slightly higher thrust model (535-E4) was created by changing turbine blades, the exhaust nozzle, and the front low pressure compressor stage. A key feature of the engine, the wide cord blade, was then transferred back to the original RB211 engine. A new engine family was then developed based on a common core, the RTM-322. Turboshaft, turboprop, and turbofan derivatives were planned based on this common core. Additionally, a scale-up of the common core was planned to produce a larger turboprop and turbofan engine. An additional example, that of Canon’s copiers, focuses on high part commonality, claiming that the copiers in a given series shared approximately 80% of their parts and that this sharing was the result of intensive research and development efforts.

Rothwell & Gardiner point out several benefits and penalties associated with a robust design approach. In addition to flexibility to future uncertainty, robust design benefits include economies of scale (shared parts), shared experience, and economies of scope (product variety). Other benefits include the retention of learning curve benefits for reused parts; inventory reduction; risk reduction; service familiarity; existing spares inventories; and customer familiarity (Rothwell & Gardiner, 1988). Additionally, the authors quote Rolls-Royce's director of technology as claiming the benefits of robust designs are economies of technology and research and development cost reduction (Rothwell & Gardiner, 1990). The most prominent penalties recognized by the authors are the lack of performance optimization associated with robust designs and the penalties associated with the creation of the initial robust design (lead variant):

> *"Unlike lean designs, robust designs take more time, resources and effort, be it in terms of labour, computer aided modeling, financing or development work. In short, robustness does not come cheap: only leanness does." (Rothwell & Gardiner, 1990, p. 283)*

One of the few identified discussions of the lifecycle benefits and penalties of commonality (Perera, Nagarur, & Tabucanon, 1999) provides a view of commonality that focuses on the benefits, with a limited discussion of penalties. The authors recognize both sharing between products and reuse between generations of the same product and they appropriately link the bulk of commonality research with sharing. The article examines component part standardization (commonality) in the context of various lifecycle phases: development, manufacturing, distribution, usage, and recycling/disposal. Trades between the benefits and penalties of commonality are not clearly explained within the article. For example, while shared economies of scale are recognized as a production benefit of commonality and the potentially increased costs of overly capable components are recognized elsewhere as a potential negative, the tradeoff between the two is unclear.

In <u>Thinking Beyond Lean</u>, Cusumano & Nobeoka (1998) address the effectiveness of four product development strategies in the context of automobile product families. Their excellent study focuses on development strategy; the relative benefits of various strategies; and on the market performance of companies employing the various strategies. The four strategies are New Design, Concurrent Technology Transfer, Sequential Technology Transfer, and Design Modification. The "New Design" strategy represents the development of a new product core in a manner that is exclusive of reuse of prior development. New Design represents radical innovation in a sense that the new design is a significant break from the past. "Concurrent Technology Transfer," "Sequential Technology Transfer," and "Design Modification" all entail incremental innovation based on reuse of existing product designs. "Concurrent Technology Transfer" entails the partial overlap of two development programs that address different market segments. "Sequential Technology Transfer" utilizes previously completed development work that was originally intended to fulfill other purposes, while "Design Modification" represents the upgrading of an existing product through minor changes.

Cusumano & Nobeoka strongly recommend the use of the Concurrent Technology Transfer strategy and demonstrate that the strategy provides reduced engineering hours and comparable lead times to other incremental advancements. Concurrent Technology Transfer creates partial overlap between programs and enables mutual adjustments, task sharing, and joint design. Mutual adjustments improve the fit of prior program decisions with the needs of the concurrent technology transfer project while task sharing and joint design reduce total development scope through shared resources (e.g., testing prototype) and shared designs. The authors conclude that

> *"Managers are better off if they leverage investments in new technology (such as through multi-project management) as opposed to not leveraging these investments at all. And they are better off if they leverage these investments quickly across markets (as in concurrent technology transfer) rather than slowly across time (as in sequential technology transfer)." (Cusumano & Nobeoka, 1998, p. 184)*

The work of Cusumano & Nobeoka suggested several opportunities for further emphasis with respect to the research presented in this dissertation. First, while the benefits and penalties of the various strategies are discussed, this discussion is not central to the book's analysis of the overall market performance of the strategies and their managerial and organizational implications. Second, the benefits and penalties of the four development strategies are primarily discussed from the perspectives of the individual products rather than from the perspective of the overall product family. For example, while the Concurrent Technology Transfer strategy appears to lead to solid market performance and product development investment controls (reduced engineering hours), limited information is provided with respect to the penalties incurred in creating the base platform that was utilized for the Concurrent Technology Transfer project. The authors show that an investment reduction is realized for the Concurrent Technology Transfer project but what about the penalty paid in a prior stage? Third, the study focuses on product development and market performance. A more precise discussion of the benefits and penalties of product development strategies in the context of lifecycle offsets is needed to improve evaluation of the alternatives.

A conference paper by Lenfle, Jouini, & Derrousseaux (2007) provides what may be the best match between the research of this dissertation and the reviewed academic literature. The authors provide an excellent discussion of the realities of platform-based development practice in the context of an automotive case study. The case study examines the auto company's challenges in developing a second generation product family from a preexisting platform. The importance of the second generation aspect of the authors' case study was the company's inability to consider this second generation during development of the initial platform for reasons such as a lack of knowledge and future uncertainty, to name a few examples. At the time of second generation development, the second generation team was left facing the challenges of reusing preexisting elements to meet initially unintended purposes. Through an example, the authors describe the development team's need to challenge the validity of existing modules and the team's proposals for design modifications to meet new requirements. The case study illustrates the challenges associated with reusing previously developed assets that did not, and could not, properly address future needs. The authors make a solid case for the dynamic, rather than static, nature of product platforms. They state the static assumption as being a limitation of the current theories. The authors also call for the need to temper the assertion that platforms always provide a benefit, given the challenges that they observed in the second generation context of their case study.

The above examples from the general management literature on product platforms and product families provide high level guidance on the development of product platform strategies and product family plans. Several summary comments are listed below.

- The management literature often approaches platform-based development as the correct approach to development and in this context, discussions of the benefits and penalties of commonality along with supporting examples tend to be positive.
- Trades between the benefits and penalties of commonality appear to have received less emphasis. For example, the management literature tends to emphasize the reduced incremental development costs, lead times, and risks associated with derivative products while deemphasizing the potentially significant investment, lead time, and risk associated with the platform or lead variant.
- Many of the benefits discussions (e.g., the benefits of shared economies of scale) are tied directly to common components, even though definitions of platforms are typically broader in scope (e.g., core capabilities and technologies).
- The literature often assumes that planning of a platform-based product family is followed by development of the core platform, then development of the lead variant (first product). As demonstrated later in this dissertation, complex product development appears to follow the Rothwell & Gardiner approach of creating a robust design that consists of combined development of the intended platform and remaining unique components in order to create the first product.
- The literature recognizes the potential for sequential development and release of new products, although the impact of lifecycle offsets is not clearly described.
- The management literature treats platforms as dynamic rather than static entities, effectively illustrating the need for change (likely divergence) in order to meet evolving market needs.

2.2.2. Quantitative Management Literature on Commonality

Several model-based approaches to evaluating the benefits and penalties of commonality were identified during the literature review. These approaches primarily come from the management science community and tend to address subsets of the overall benefits and penalties of commonality due to the complexity of the overall topic and the difficulty of modeling this complexity. Creating a full model of commonality would entail modeling the lifecycle phases of the product family from the manufacturer's perspective at a minimum. As a result, sub-areas have been investigated; for example, the inventory benefits of common versus unique components.

Fisher, Ramdas & Ulrich (1999) provide an excellent, measured discussion of the benefits and penalties of using common components, which they refer to as "component sharing." They address components that are weakly related to customer perceived attributes, enabling analysis of cost and the omission of revenue. The authors recognize the prevalence of reuse and the fact that most industrial decisions require a decision between reuse and new components. They state the potential benefits of commonality to be lower development costs and lower fixed costs of production (i.e., manufacturing tooling expenses) through reduced total development scope. Additionally, they recognize potential benefits in areas such as inventory, materials procurement, and quality assurance that are tied to commonality-driven reductions in the superset of components supported by a given company. Increased costs of coordination associated with common development are mentioned but not incorporated into the study.

Trades between key factors are discussed in the article. The authors recognize that commonality may either lead to an increase or decrease in variable costs due to the trade between shared economies of scale and the potential costs of excess capability. They also recognize that the performance of common components may be increased or decreased: increases may arise due to the ability to make increased investments in common components, while decreases could result due to holistic product performance impacts.

The authors provide several findings based on their development of a mathematical model that is applied to an automotive brake example. Increased differences in required capability drive increased numbers of component types (i.e., increasing uniqueness of the product designs). Increased production volumes also drive increased numbers of components due to the ability to amortize development costs across more units. Increased variability in component production volumes drives decreased numbers of component types; i.e., higher levels of commonality: products with lower production volumes have stronger incentives to utilize components that were optimally designed for other products.

Ramdas, Fisher, & Ulrich (2003) provide a model-based examination of the impacts of three organizational structures: coordinated projects, independent projects, and partially coordinated projects. Within the framework of these three structures, they examine the relative benefits and penalties of commonality in components that do not have a strong impact on customer differentiation. This assumption allows analysis of cost and omission of revenue.

The coordinated/uncoordinated project dilemma is well explained by the following quote:

> *"In the project-by-project approach, each car design team would independently select a feasible braking system with the lowest sum of fixed and variable costs, even if demand were very low. This would lead a team to design a braking system that is "just adequate" over using a better than adequate system, even if the latter would need to be designed in any case, for a heavier car. Doing this ignores potential savings that would accrue if the incremental variable cost from using the better than adequate system were lower than the fixed cost for the just adequate system." (Ramdas, Fisher, & Ulrich, 2003, p. 151)*

The optimization model assumes that the platform architecture has been predetermined and that projects must select from a possible set of existing and potential new components. These decisions are either made jointly (coordinated project) or independently. A high degree of rationality is assumed in decision making: teams are aware of all existing component versions and potential new versions and teams know all fixed costs, variable costs, and sales volumes.

The model provides several insights into the benefits and penalties of commonality. The benefits of coordinated projects are shown to increase with increasing design costs (fixed costs), complexity costs, and warranty costs. Benefits are also shown to increase with the number of potential design options because chance is less likely to produce commonality; especially in the real world of infinite choices for new designs. The model also shows that coordinated projects may select options that appear to be irrational from the myopic view of an independent project.

Three apparent limitations of the model are important to note for the purposes of this dissertation. First, in the case of independent projects, the decision by more than one project to develop the same component results in only one fixed development charge. This seems to be a weakness of the model as real projects incur multiple charges for developing essentially the same part multiple times, an outcome recognized by the authors (Ramdas, Fisher, & Ulrich, 2003, p. 150). Second, the model considers variable part cost to be fixed, meaning that shared economies of scale benefits are ignored. Third is a lack of consideration of lifecycle offsets between projects. The result of the first two limitations is an increased optimism in the valuation of independent projects in relation to those with coordination (commonality). The lack of offset consideration appears to be acceptable for the auto example studied in the paper, although lifecycle offsets may impact the realized benefits and penalties of commonality, as discussed in later chapters of this dissertation.

Ulrich & Ellison (1999) discuss the decision to reuse existing components ("select") versus design new components ("design") that are optimized to meet the needs of a current program. Their research represents one of the few examples of direct consideration of lifecycle offsets that was identified during this literature review. The authors' research approach included theory and hypothesis development followed by empirical hypothesis testing using a survey that returned information about 225 products. A very broad range of product types is represented in the survey data. (Refer to Ulrich & Ellison, Table 1, p. 649.) Stated benefits of reuse include minimized investment in development and tooling, economies of scale in production, and the ability to focus efforts on core capability development through reduced total development scope. Benefits of new design include meeting holistic performance requirements and the reduction of variable costs through the avoidance of excess component capability and the use of integral architectures. The authors explicitly state that for a given production quantity, the "true variable cost of production" of a new design (optimized) component will be lower than a reused component.

The authors assume that organizations act rationally with respect to the design-select decision stating that "a firm will not design a component when an adequate substitute already exists." Two stated caveats to being able to consider reuse are the need for a component that did not previously exist and a company's lack of knowledge regarding the existence of a part. The author's consider both of these caveats to be transient.

Krishnan and Gupta (2001) present a widely cited paper that provides an objective discussion of the benefits and penalties of commonality from the view of profitability and a profit model that provides additional intuition in the context of a two product family. The model compares a two product, platform approach to the alternatives of addressing both market segments with either one or two independently designed products or simply addressing one segment with one product. The model does not address the potential dynamic nature of the underlying platform, although this modification could be incorporated into the model. The impact of lifecycle offset is investigated for the specific case of high capability model introduction followed by introduction of a lower capability model. Key factors investigated in the paper include integration benefits, overdesign costs, and economies of scale. Differences between required product capabilities and production volumes are also discussed. The model provides useful insights from the standpoint of revenue and cost impacts and also highlights a critical aspect of commonality: broad generalizations about the benefits of commonality in relation to independent approaches are difficult to identify. Many of the observations in Krishnan and Gupta's paper are tied to trades between model factors. For example, platforms *may* increase profitability over independently designed families depending on the degree of realized scale economies and overdesign penalties.

In an earlier paper, Krishnan et al. (1999) present an excellent discussion and model-based analysis of the benefits and penalties of platforms from the standpoint of sequential variant development: the initial platform is developed, then the initial variant, then follow-on variants.[10] Like the later model from Krishnan and Gupta (2001), profitability is the end analysis goal and the planning phase of product family development is targeted. The authors recognize the large upfront investment (monetary and time) required to create a platform, an investment that is sometimes underemphasized in the general management literature. The trade between this investment and expected future savings is discussed: as platform scope increases, reductions in individual product development scope are expected, along with reduced development costs. Additionally, the authors clearly recognize the trade between economies of scale benefits and increased costs associated with excess capability. Variable costs are viewed as situation specific, rather than being set up to exhibit net benefits due solely to economies of scale.

Krishnan et al. (1999) classify product costs into three conceptual categories: unique to a given product; adapted from a prior product; and shared between variants (the platform). Platform components are common across all models of the family and are assumed to be selected during initial product family planning, and then implemented with certainty; i.e., the platform does not change during the product family history. While some product modules are modified, these adaptations are pre-planned rather than emerging. All associated costs, including those associated with the platform, are assumed to be known a priori with certainty. For example, adaptation is expected, defined, and part of the product family plan. The special case of increasing performance with each new product model is addressed, with the assumption that the products vary along only one attribute.

[10] The authors explicitly recognize other alternatives such as simultaneous development, although these alternatives are not addressed by the model.

The models and empirical study discussed above add rigor to the benefits and penalties discussion, although they do not represent the "final answer," due in part to limitations in scope. For example, the models examine either reuse of preexisting components or sharing of new development but not both. The partial exception to this statement is the Ramdas, Fisher, & Ulrich (2003) model which assumes that programs can select from pre-existing components or new components, which may be shared. Additionally, the models reviewed as part of this research do not typically address changing commonality strategies over time. The model literature appears to assume that the platform is developed and then remains stable throughout the product family lifecycle; the model of Krishnan et al. (1999) excepted. The general management literature on product platform renewal (e.g., Meyer & Utterback, 1993) and the evidence presented in the case studies associated with this dissertation both suggest that the assumption of a static platform is unrealistic. Platforms change and changes in these platforms may have significant impacts on the realized benefits of pursuing development of Intended Common components.

2.2.3. Engineering Design and Optimization Literature

The large body of engineering literature tends to be focused on the presentation of new methods for the design and optimization of product families, with cursory treatments of the benefits and penalties of commonality often being presented in order to motivate the need for a new method. The proposed methods are often applied to an example problem in order to demonstrate their utility. Results are typically discussed in an application-specific context.

Simpson's widely cited product platform review article (Simpson, 2003) points out three common assumptions made by the developers of platform optimization methods: maximizing product performance maximizes demand; maximizing commonality minimizes production cost; and product family profitability results from properly trading these two objectives. The assumed relationship between commonality and cost is simplistic based on the review of the management literature (e.g., the cost of excess capability recognized in Meyer, 1997 and Fisher, Ramdas, and Ulrich, 1999), meaning the methods may lead to decision making errors. This apparent limitation can be viewed as a direction for future work, rather than a fundamental limitation of engineering design methods: a more complex relationship between commonality and cost could be incorporated into the models.

Economic evaluation is sometimes included in the engineering models, although Table 1 in Simpson's review article (Simpson, 2003) indicates that only half of the listed engineering algorithms (16 out of the 32 presented in the table) incorporate product family economics in some manner and that only a quarter (8 out of 32) consider both revenue and cost. For example, consider the widely cited paper by Simpson, Maier, & Mistree (2001) that describes a platform design method ("Product Platform Concept Exploration Method") and the application of this method to a universal electric motor application. The paper focuses on the analysis of technical options for commonality and the performance penalties associated with these options in relation to independently optimized designs. Through analysis of multiple platform strategies, the authors demonstrate the trade between performance and commonality: reducing commonality leads to increased performance of each variant with respect to individual market niche requirements. Determination of the proper level of commonality is left to external economic analysis since economic analysis is outside the scope of the design methodology.

The following references have addressed the coupling between platform-based product family design and economic evaluation to varying degrees and have also discussed the benefits and penalties of commonality, again, to varying degrees. Most of the references have made a very strong connection between economics (either profit or cost) and design decisions. The papers included below represent the strongest identified matches between the existing literature and the research presented in this dissertation.

The realities of platform-based product development are well-represented in the "pseudo-optimization" framework presented by Gonzalez-Zugasti, Otto, & Baker (2000). The framework calls for the comparison of platform-based alternatives to the independent design alternatives they would replace. While a mathematical description is presented, the authors state that the availability of models of complex systems is rare and that teams are often best prepared to "optimize" platform designs through collaboration and negotiation. The benefits and penalties of commonality are discussed in general terms. Additionally, the potential value of reuse is recognized, a rare acknowledgement in the engineering design literature that tends to approach development of a product family as a clean sheet exercise.

Gonzalez, Otto & Baker (2001) present a platform family valuation method that couples with the design framework presented in Gonzalez-Zugasti, Otto, & Baker (2000). The valuation method assumes an initial investment is made in a platform, followed by potential future inclusion in product designs. Uncertainty is considered in several areas of the valuation method: the success of the initial platform investment; the platform fit with the needs of each variant; the incremental development costs for each variant; and the benefit of using the platform over the alternative of independent development. The method assumes that a group of acceptable platforms is selected and then subjected to future uncertainties in order to pick the best platform design. The method appears to take an "all or nothing" approach to reuse of an existing platform: each program has the option of utilizing the existing platform or rejecting it. Typically, the decision to use a platform is one of degree in the "real world." Platform decisions are reversible in a sense that additional investments can be utilized to modify the platform to meet the needs of the current program. These investments are likely to be smaller than the alternative of new development that replaces the entire platform.

The authors (Gonzalez, Otto & Baker) tangentially address lifecycle offsets and divergence. The authors examine the case of platform development, followed by sequential development of the product family variants. Although they recognize two alternative situations, parallel development of multiple variants and the simultaneous development of the platform and first variant, they do not discuss the ramifications of these alternatives. The article also represents one of the closest identified matches between the reviewed literature and the phenomenon of divergence.

Suh, de Weck, & Chang (2007) present a Flexible Platform Development Process that addresses the identification and economic valuation of opportunities for flexibility within product platforms. The authors introduce the concept of flexible elements as an alternative to common and unique elements. Flexible elements are defined by the authors to be elements that have lower costs of modification in comparison to their unique alternatives. The development process proposed in the paper entails identifying, valuing, and comparing different flexibility strategies in light of future uncertainties and a portion of the process involves design optimization for economic return. The authors recognize a potential weakness of their method as being the need to select the "right" uncertainties that may influence a given product, or more specifically, a given component design. Unlike the majority of engineering design studies reviewed during this dissertation research, this paper explicitly recognizes the potential for platform change in the lifecycle of the product family and takes this into account in the design and evaluation of the benefits and penalties of alternatives. The shift from a static to dynamic view of the product platform is a critical contribution to the engineering literature and is well-aligned with key managerial insights (e.g, Meyer and Utterback, 1993).

Fujita et al. (1998) provide a conceptual and optimization framework for product family development that considers product family profitability given factors such as the degree of commonality between designs, production volumes, and economies of scale. The framework assumes the simultaneous development of all product family variants and does not consider lifecycle offsets. The framework consists of selection of a system architecture (modules in the system), followed by optimization of module attributes in order to meet product-specific requirements. The authors recognized "independent", "similar," and "same" designs. "Independent" designs are determined completely independently from other products and are expected to have different attributes. "Similar" designs share attributes that may produce benefits such as enabling common manufacturing processes. "Same" designs are directly shared across products. The paper examines the relationship between the design tactics (independent, similar, and same) and the relative differences in product characteristics. For example, independent designs are stated to have a development cost disadvantage in comparison to same designs when product characteristics are very similar. Also, same designs are stated to have an operational cost penalty as product differences increase. The authors also discuss trades when selecting concepts. For example, they describe the importance of the ratio between Non-Recurring Engineering (NRE) and production costs in selecting a design concept for a single product, although the concept is not extended to a multi-product view. Production volume sensitivity is also discussed, although the discussion appears to target scaled production volumes as opposed to differences in the relative production of two or more product variants.

Fujita and Yoshida (2001) build upon the method and cost model of Fujita et al. (1998) through the use of a hybrid optimization algorithm. The authors apply their method to the conceptual design of an aircraft family that considers different cases of high level requirements (range and passengers). As with Fujita et al. (1998), the model and its application assume simultaneous development of the product family members. In production, each member of the product family is assumed to have the same demand: relative demand changes are unexplored. An included example illustrates the benefits of commonality through a profit calculation. The article provides a discussion of product family design outcomes and rationale in the context of an airplane example.

Fujita (2002) summarizes prior work by Fujita et al. (1998 and 2001) and also provides additional discussion of cost structures and the benefits and penalties of commonality within these cost structures. For example, learning effects are stated to reduce production costs with increasing unit production history, while the cost of over-specification is listed as a negative. The paper describes a trade between the decreasing development costs associated with increasing commonality and the increasing production costs.

Umeda et al. (1999) present a framework that addresses the topic of upgradable designs and in doing so, addresses the issue of product timing. The framework classifications are “traditional independent design” (independent development without reuse); “series design” (sequential, independent development with reuse); “upgrading design” (platform-based development with Intended Common components); and “upgradable product design” (“upgrading design” with proactively enabled retrofits of in-service products). The authors explicitly address sequential development, which entails upfront planning of a product family, followed by sequential development based on this plan.

The methods and applications focus of the engineering design literature makes the extraction of generalized insights into the benefits and penalties of commonality somewhat challenging, as these insights are often couched in the context of a specific application such as the design of a consumer product or aircraft family. Additionally, introductions to individual papers tend to present generalizations about the benefits and penalties of commonality by way of motivation for the need for an improved method. The combination of context-specific application discussions and generalizations may contribute to confusion about the true benefits and penalties of commonality.

Two additional factors limit the explanatory power of the reviewed engineering literature with respect to the benefits and penalties of commonality. First, lifecycle offsets are not clearly addressed. Some authors such as Fujita et al. (1998) and Li & Azarm (2002) address aligned product lifecycles, either explicitly or implicitly. Others recognize some degree of lifecycle offset. For example, Gonzalez-Zugasti et al. (2001), address development of a platform, followed by sequential development of derivatives. While they recognize the potential for lifecycle offsets, they do not discuss the implications of these offsets. A second important factor is the fact that, unlike the management literature, much of the engineering design literature tends to treat the platform as a static entity. For example, Gonzalez-Zugasti et al. (2001) provide a decision tree method that provides a choice between use and rejection of an existing platform for the development of each individual variant. Suh, de Weck & Chang (2007) and Allada and Jiang (2002) provide the best identified examples of changes being made to the core underlying platform in response to needed future changes.

2.2.4. Literature Summary

The literature on commonality addresses a broad range of topics including the creation of product family strategies and their accompanying designs. Underemphasized in the literature is guidance on the actual benefits and penalties of commonality in relation to the alternative of independent development. This statement is supported by a recent review paper on product families and platform-based development (Jiao, Simpson, & Siddique, 2007), as no papers focusing on the benefits and penalties topic were identified. Without a clear understanding of the benefits and penalties of commonality, evaluating opportunities for commonality is relegated to a series of “hip shots” that may have major implications for product family profitability.

At a more detailed level, limited insight was gained into the concept of lifecycle offsets. This topic does not appear to be well-addressed in the literature, yet it plays a critical role in properly assessing and realizing the benefits of commonality as discussed in Chapter 6. The best example of the consideration of lifecycle offset in the general management literature comes from the development program characterizations of Cusumano & Nobeoka (1998). The management science community has provided models that deal with either parallel programs (typically an implicit assumption) or reuse, but rarely both. The exception is Ramdas, Fisher, and Ulrich (2003) which addressed reuse and the potential for sharing. The engineering community typically assumes parallel development, although Gonzalez-Zugasti et al. (2001) provides a counter to this statement.

The literature review also provided limited insight into the phenomenon of divergence. The management literature clearly recognizes the dynamic nature of platforms and explicitly calls for continuous renewal of platforms as an imperative for profitability (e.g., Meyer and Lehnerd, 1997; Meyer and Utterback, 1993) but does not discuss the implications of this renewal from the perspective of the benefits and penalties of commonality. Only beneficial change appears to be recognized by the management community, although as discussed later in this dissertation, undesirable changes may occur and may cause penalties. The potentially negative impacts of change are recognized in the case of independent development programs, yet do not appear to be believed to be applicable to platform-based development. In regards to independent development, Meyer and Lehnerd state the following:

> *“Diversification is often unplanned; products and product lines are added one product at a time and without the benefit of overarching strategic principles. Typically, the additional products create greater complexity in manufacturing, procurement, and distribution, and the attention of senior managers is consumed in managing that complexity.” (Meyer & Lehnerd, 1997, p. 52)*

> *“Unfortunately, this fragmented platform approach is common in industry. Seeking to build the perfect product for each new customer group, engineers lead the corporation away from commonality. Each time a new customer is formalized, new parts are added to achieve the optimum solution without consideration of the downstream costs of the decision…As the components of the*

firm's products proliferate- be they motors, fasteners, or whatever- opportunities to achieve economies in procurement diminish." (Meyer & Lehnerd, 1997, p. 56)

This dissertation indicates that Meyer and Lehnerd's admonishments about independent development and the diversification of independent designs apply to platform-based product development as well. Non-value added costs are incurred, just as in the case of independent development. Failure to account for and manage these costs results in over-optimism about the benefits of commonality.

Unlike the management literature, the engineering literature almost universally assumes that platforms are static (e.g., Simpson et al., 2001). Once the platform has been determined, it is assumed to be constant for the lifecycle of the product family. The case studies within this dissertation show that this outcome is unlikely in the context of complex product lifecycles and has implications for the benefits and penalties of commonality. Suh, de Weck & Chang (2007) provide a notable exception to the static platform statement given their examination of flexibility in platform design.

The limited research on the general benefits and penalties topic and the more specific topics of divergence and lifecycle offsets, has been the inspiration for this research. The perceived importance of these topics; the limited theoretical foundations associated with divergence and offsets; and the perceived complexity of these topics drove the decision to pursue field research. Prior to the field research methods discussion, a list of factors influencing the cost benefits and penalties of commonality is discussed below. The factors were based on the findings of the literature review and serve as a useful foundation upon which to build an understanding of the impact that divergence and lifecycle offsets have on the overall benefits and penalties of commonality.

2.3. Factors Influencing the Cost Benefits and Penalties of Commonality

The literature review was utilized to create a list of key factors that can be used to describe the influences that commonality has on a product's cost structure. These factors are discussed in terms of the development, production, and operations phases of the product lifecycle and support the simple model discussed in Chapter 6. It is important to keep in mind that these three phases have different relative costs and that these differences can be critically important in determining the decision making emphasis of a given program. Shifting emphasis in decision making influences many types of product development decisions, including those associated with commonality.

2.3.1. Development Costs

In this dissertation, development costs are assumed to include engineering development, procurement, testing, and tooling (e.g., production equipment). These non-recurring expenses are treated as a lump sum. Key factors influencing the cost of development are development scope, common development penalties, and learning benefits. Development scope refers to a measure of the total amount of work that must be completed in order to develop the members of a given product family. Development scope reduces as commonality between product family members increases (Figure 9). This scope reduction may be partially offset by a penalty that is associated with developing the common components. The penalty may be due to true increases in design complexity (e.g., the addition of interfaces to a common design) and to coordination costs. Coordination costs arise from the need to agree on a superset of requirements that represents the minimal needs of all products that will share a common component. The functionality of a given part or module is likely to be very similar across product family members, with adjustments being made to the attributes of these functions rather than to the functions themselves. Learning represents a third development cost category. Learning reduces the effort associated with repeating similar tasks. The existence of learning curve benefits implies time separation between tasks, which is typical in sequential development.

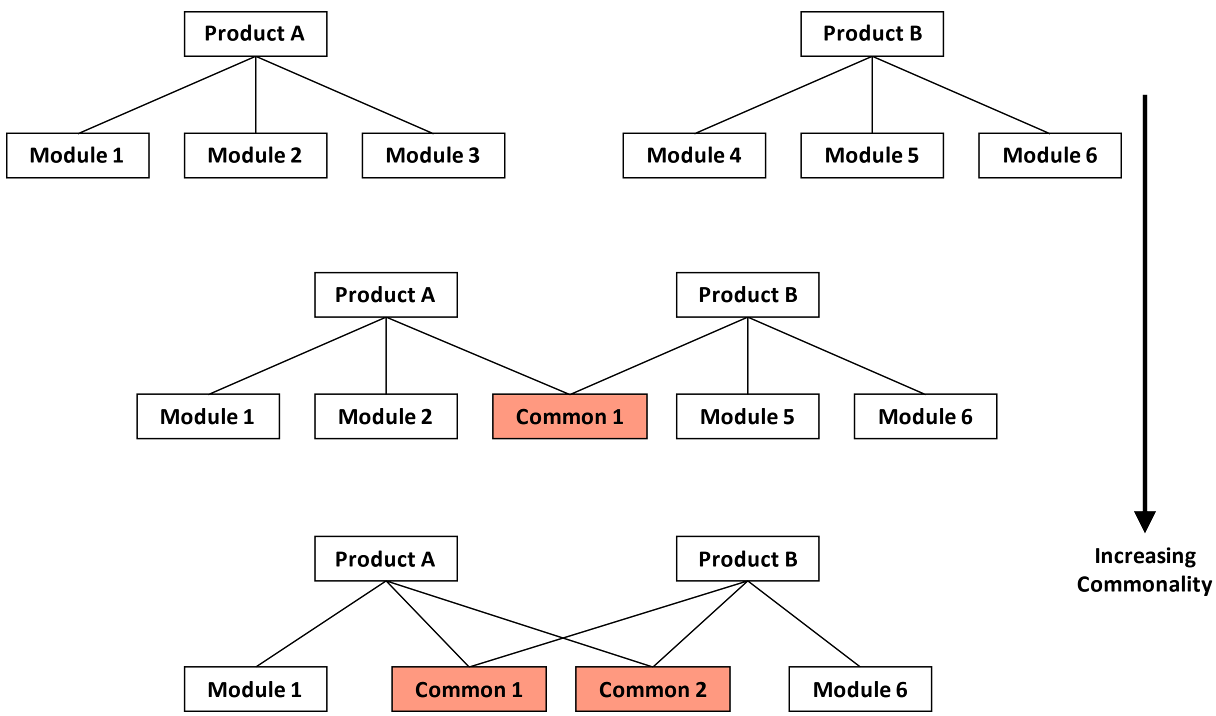


Figure 9: Increasing commonality decreases the total scope of development. The scope reduction is partially offset when common modules are more complex than the independent modules they replace.

The literature often suggests that a net development cost reduction is expected for the product family. For the most part, it is acknowledged that developing the lead variant (first product and platform) will cost more than the independent alternative because a set of Intended Common components is being developed with the intent of future reuse across the members of a product family. Follow-on variants are expected to cost less to develop due to reuse of the Intended Common components.

2.3.2. Production Costs

Production costs can be broken down into direct and indirect costs. Direct costs include materials (the dominant cost for systems integrators such as those discussed in this dissertation) and labor. Materials costs are related to the capability of a component; the component's cumulative production history; and the component's production rate. Component capability can be thought of as determining the Theoretical First Unit (TFU) cost of a given component, although this cost is truly the combination of component capability, supplier technology, and supplier margin. That said a component with more capability is likely to cost more. As a simple example, structural component costs are partially attributed to the amount of metal they contain. A stronger component requires more material for a given geometry and material type. Indirect costs represent overhead and consist of expenses such as facilities maintenance and managerial oversight associated with manufacturing. Direct and indirect production costs are discussed in more detail below.

Labor is related to overall task complexity and is typically expected to reduce with increasing cumulative production totals. The labor reduction is the result of learning that occurs through the repetition of the same tasks. The learning curve is described by Equation 2.1 (Newnan, Eschenbach, & Lavelle, 2004).[11] This equation states that the labor for the Nth unit, T_N, is related to the product of the labor for the first unit, $T_{initial}$, the production unit number, N, and the learning curve exponent, b. The learning curve exponent is described by Equation 2.2. The learning curve input is a decimal value that indicates the remaining labor, given a doubling of cumulative production. This input value may range between 0 and 1, with typical values being between about 0.75 and 0.95 (NASA Cost Estimating Handbook, 2004).

$$T_N = T_{initial} \times N^b \tag{2.1}$$

$$b = \frac{log\,(learning\ \ curve\ \ as\ decimal\ )}{\log 2.0} \tag{2.2}$$

An 80% learning curve is illustrated in Figure 10. The rate of improvement diminishes with increasing cumulative production: the greatest learning is achieved during production of the first unit. High volume products, such as consumer products, quickly reach the flat portion of the curve and the actual learning curve effects represent a transient inefficiency associated with startup. In the case of complex products such as aircraft and satellites, production volumes are much lower and the learning curve has a higher degree of importance throughout the lifecycle of the product family. With respect to commonality, common components create aggregate demands that drive labor costs down the learning curve at a faster pace and, potentially, to a lower end point.

[11] The original source of the learning curve concept appears to be Wright (1936), "Factors Affecting the cost of Airplanes."

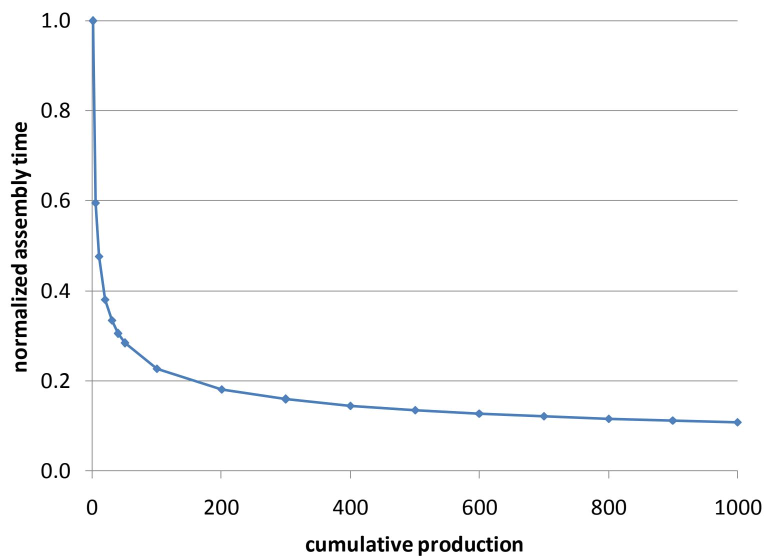


Figure 10: Assembly time reduces with cumulative production. An 80% learning curve is illustrated.

Material costs decline with cumulative production history and production rate. Cumulative production creates learning curve benefits that are realized in the labor portion of the materials cost.[12] This cost savings may be passed along to the system integrator in the form of a component cost reduction. Additionally, the rate at which a component is procured impacts the component's production costs and supplier pricing. Costs are likely to decline with increasing rates, an outcome referred to as economies of scale. There are two factors that influence this outcome: the relative importance of fixed versus variable costs and a supplier's approach to profitability. Fixed costs are assumed to be constant regardless of the production rate,[13] while variable costs are incurred on a per unit basis. Figure 11 illustrates the relationship between the two for a hypothetical example.

Also important in understanding realized economies of scale is the distinction between the underlying cost structure and a supplier's approach to profitability. A supplier may attempt to maintain price in light of increasing volumes, increasing both gross margin (a percentage of unit price) and gross profit. An alternative approach is to maintain gross margin. A third alternative for a supplier that is only concerned with increasing gross profit is to accept margin reductions while still achieving the goal of increased profits. Figure 12 illustrates the cases of constant gross margin and constant gross profit. Prices above the constant gross profit line but below the constant gross margin line represent increasing gross profit but at declining gross margins. Prices above the constant gross margin line represent increasing gross profits and margins. The

[12] In complex systems with high levels of supplier integration and "long" supply chains, learning curve benefits are incurred at multiple points in the supply chain. A systems integrator's materials costs may contain significant amounts of labor due to the value-added work of the supply chain. If there are significant time gaps in production, the learning benefits may be partially lost. Example: the elimination of an experienced assembly team that must later be replaced by a less experienced team.

[13] There is actually a limit. Fixed costs are "fixed" until existing production capacity has been fully utilized. At that point, production line expansion is required and this expansion requires both initial investment and increased fixed costs in support of annual operation of this higher capacity plant.

end result: prices paid by a systems integrator are expected to decrease with increasing purchase rates (units/year) but these benefits produce diminishing returns. The actual price paid by a systems integrator depends on the component design, the supplier's cost structure (fixed and variable), and the supplier's pricing strategy.

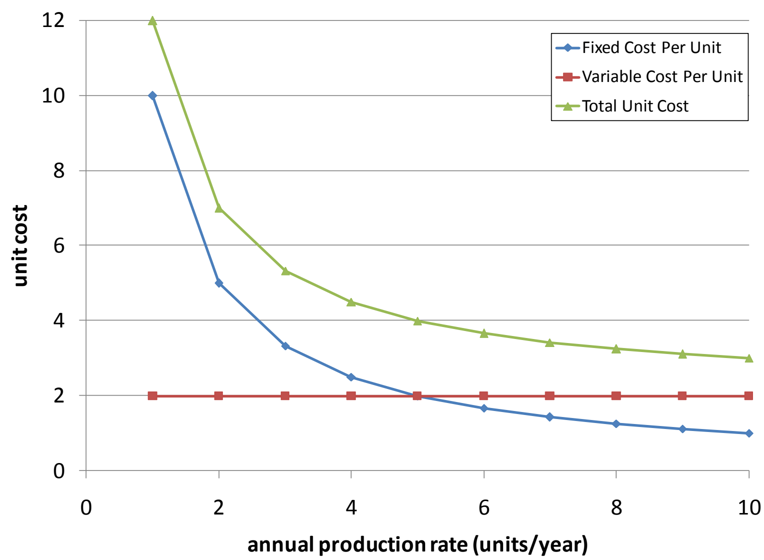


Figure 11: An example of the relationship between production rate and fixed cost per unit, variable cost per unit, and total cost per unit. The decreasing total unit cost trend is the result of amortization of fixed costs across increasing annual production.

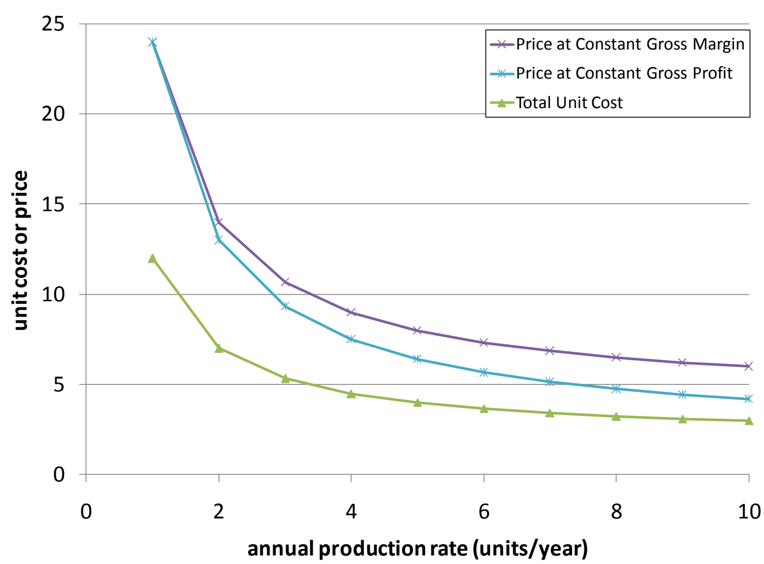


Figure 12: Example pricing curves are illustrated for fixed gross margin and fixed gross profit. A supplier may be willing to accept lower gross margin given higher gross profit. The area between the two profit curves represents this decision space, which widens with increasing production rate. The Total Unit Cost curve is included for reference purposes.

Common materials may impact production costs in several manners. Shared economies of scale result from the combined production rates of simultaneous production of more than one product (Figure 13). Additionally, accelerated learning curve benefits may be passed on to the manufacturer from the supplier. The learning benefits are accelerated by increased production numbers and potentially by higher production rates, given overlapping production. The benefits of economies of scale and learning curve traversal are traded against the negative "fundamental costs" associated with overly capable parts, as recognized by researchers such as Fisher, Ramdas, & Ulrich (1999) and Krishnan et al. (1999). The cost model of Chapter 6 assumes that materials costs are influenced solely be economies of scale and that all learning is recognized through internal labor cost reductions.

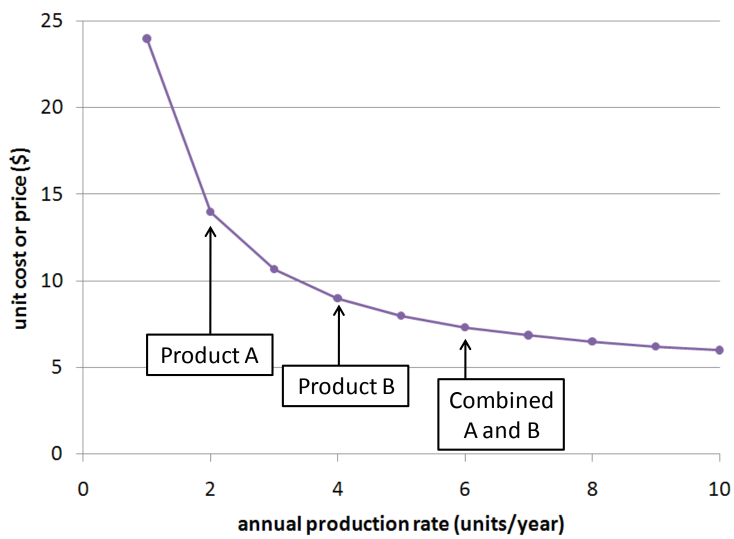


Figure 13: Aggregate demands for common parts create procurement savings due to shared economies of scale.

The third component of production cost is indirect cost (also referred to as "overhead"), which represents those costs that are not directly attributed to materials and labor. Examples of overhead costs include annual facilities costs, inventory holding costs, and managerial time. A typical approach in industry is to compute all overhead costs and then to assign them based on direct-labor hours, direct-labor cost, direct-materials cost, or total direct cost (Newnan, Eschenbach, & Lavelle, 2004). Commonality may reduce overhead costs through inventory level reductions and through overall complexity reductions although a trade exists. This benefit has been debated by researchers as summarized by Labro (2004).

2.3.3. Operations Costs

Operations costs can be divided into direct operating costs and maintenance costs. Direct operating costs are the charges incurred with normal operation of a product. For example, direct operating costs associated with an aircraft include fuel and crew charges. These costs are incurred by the system operator (e.g., the customer) which is typically a different entity than the manufacturer. Maintenance costs are the result of required upkeep on the product. At a high level, maintenance costs have a similar structure to production costs: materials are consumed; labor is required; and overhead charges result from facilities, inventory, and management.

2.3.4. Cost Factor Summary

The costs and modifying factors discussed above are summarized in Table 1. This framework is utilized in later discussions of the influences of divergence and lifecycle offsets on the benefits and penalties of commonality. Each of the high level cost categories from Table 1 (left column) can be further decomposed in a number of ways. One generic cost structure is included below in Table 2, along with a notation that indicates whether or not the simple model of Chapter 6 addresses the category. As indicated, the simple cost model developed in Chapter 6 addresses development costs and the variable costs of production. Sub-categories (e.g., “Engineering” development) are not explicitly addressed by the model.

Table 1: Cost categories by lifecycle phase. The categories are impacted by the degree of commonality between product family members.

Lifecycle Phase	Cost Sub-Category	Modifier
Development	Development	Scope (Total = New + Reuse)
		Coordination Costs
		Learning Curve Benefits (Cumulative History)
Production	Materials	"Fundamental" Cost of Capability
		Economies of Scale Benefit (Rate)
		Learning Curve Benefit (Cumulative History)
	Labor	Learning Curve Benefit (Cumulative History)
		Complexity
	Overhead	Various
Operations	Direct Operating	Design Attributes
		Input Pricing (e.g., fuel, labor)
	Maintenance- Materials	Same as production
	Maintenance- Labor	Same as production
	Maintenance- Overhead	Same as production

Table 2: A generic lifecycle cost structure. The right hand column indicates whether the factor is included in the Chapter 6 cost model. The simple model only addresses cost subcategories (e.g., "Engineering") in a generic manner. Operations and overhead are not addressed by the model.

Cost Cateogies	In Model?
Development (Non-Recurring)	
Research	Yes
Development	Yes
Engineering	Yes
Engineering Test	Yes
Manufacturing Facilities, Equipment, Tooling	Yes
Maintenance & Upgrade Facilities, Equipment, Tooling	Yes
Training- Manufacturing and Maintenance & Upgrade	Yes
Production (Recurring)	
Direct Production (variable)	
Materials	Yes
Labor	Yes
Delivery	No
Production Overhead ("fixed")	
Facilities	No
Inventory	No
Management	No
Operations (Recurring)	
Direct Operations (variable)	No
Operations Overhead ("fixed")	No
Direct Maintenance & Upgrade (variable)	
Materials	No
Labor	No
Maintenance & Upgrade Overhead ("fixed")	
Facilities	No
Management	No
Inventory	No
Retirement	No

2.4. Chapter Summary

This chapter has presented relevant background material for the remainder of this dissertation. Frameworks were presented for lifecycle offsets and for the classification of groups of components by commonality intent and outcome. The literature review emphasized the potential opportunity to contribute to an understanding of divergence and lifecycle offsets and to the broader topic of the benefits and penalties of commonality. Additionally, the simple cost framework of Section 1.3 provided relevant background in support of the model of Chapter 6.

3. Field Research Methods

3.1. Introduction

The literature review provided some insight into the benefits and penalties of commonality in comparison to independent development and also provided limited insight into the specific topics of divergence and lifecycle offsets. As was mentioned previously, two main hypotheses were created as a result of the literature review and as a result of the opportunities identified during this review.

- Divergence, or the tendency for commonality to decline over time, is typical in complex product families. Divergence reduces the benefits of commonality and has a negative impact on product family profitability.[14]
- Lifecycle offsets are common in complex product families. Offsets negatively impact the benefits and penalties of commonality and industrial approaches to commonality in general.

In order to better understand the above hypotheses and the more general topic of commonality in complex product families, the decision was made to conduct a series of case studies, each of which examined the development history of a complex product family. While the main objective of the case studies was to better understand divergence and lifecycle offsets and their impact on the benefits and penalties of commonality, the scope of the multiple-case study was broad. At the highest level, each case study attempted to understand and document the product family history with emphasis on the evolution of commonality over time. The case studies provided insights into the evolution of the product families and the evolution of commonality within these product families; the managerial actions that influenced commonality (both intended and unintended); and the perceived benefits and penalties of commonality. The case studies provided a window into complex product family development practice and provided a rich context for understanding the realities of commonality.

The field research was initially guided by the following high level questions.

1) How does commonality change over time in complex product families? What are the sources and enablers of this change? What impact do these changes have on the benefits and penalties of commonality?
2) Do lifecycle offsets exist in practice? What impact do these offsets have on the benefits and penalties of commonality? How do these offsets impact approaches to commonality?
3) What are the economic benefits and penalties of commonality, as perceived by industry? What are the key influencing factors?
4) How do management actions influence commonality in the context of potential lifecycle offsets and changing commonality?

[14] The reader is reminded that the field research indicates that this initial hypothesis is wrong. Divergence *may* have a negative impact on product family profitability.

3.2. Field Research Design

A multiple-case study format was selected to investigate the state of platform-based development practice. Case studies are a useful method for investigating contemporary phenomena in their real world context and benefit from theoretical propositions for guidance (Yin, 2003). As the name suggests, a multiple-case study consists of several individual cases, each of which is conducted independently and sometimes even conducted by different researchers (Stake, 2006). A cross-case analysis is then performed on the individual cases in order to produce cross-case findings that aid in better understanding the central topic or "quintain" as Stake refers to it. The balance between the objectives of the cross-case analysis and the specificities of the individual cases is a source of constant tension during any multiple-case study (Stake, 2006). In this research, generalized findings about the high level themes have been emphasized over the unique aspects of the individual cases. The individual cases have contributed to the high level themes while also providing specific examples in support of and refutation of generalized observations.

The multiple-case study design employed mixed methods, qualitative and quantitative, for analyzing the individual cases. The intent of a mixed methods study is to leverage multiple sources of information in order to improve a researcher's confidence in findings through both triangulation of information and compensation for biases or weaknesses of a given method (Creswell, 2003). Interviews were the primary source of qualitative data for each of the studies. When available, quantitative product data was also obtained and analyzed.

In this research, each individual case study represents a complex product family history. The individual cases were selected from a broad range of industrial sectors (e.g., aerospace, automotive, and high tech) with the common theme being the company's pursuit of some degree of platform-based development. The intention of the broad selection of cases was to gain a general understanding of commonality in different contexts, rather than to characterize a specific industry.

Selection of the individual cases was the result of a compromise between research goals and the practical considerations of access. Out of the nine organizations approached to participate in the study, seven organizations accepted. One rejection was obtained from a government organization that was unable to accept an unsolicited proposal and the second rejection came from a large military program that was concerned about information security. The high acceptance rate for study participation provided a good check on the industrial relevance of the topic of commonality: industry is interested in the topic of commonality and challenged by its evaluation and management.

The high level case study process entailed overall study design, case selection, individual case study execution, and cross-case analysis. The general process flow from case study execution forward is illustrated in Figure 14. This figure also delineates the case study outputs as utilized later in this dissertation. Outputs from the individual cases included confidential case study reports for each participating company and a publicly released version of the case study report that is either presented in Chapter 4 or included in the Appendix. The cross-case analysis led to general observations about the realities of commonality in industry and contributed substantially to the detailed descriptions of divergence and lifecycle offsets that are contained within this dissertation.

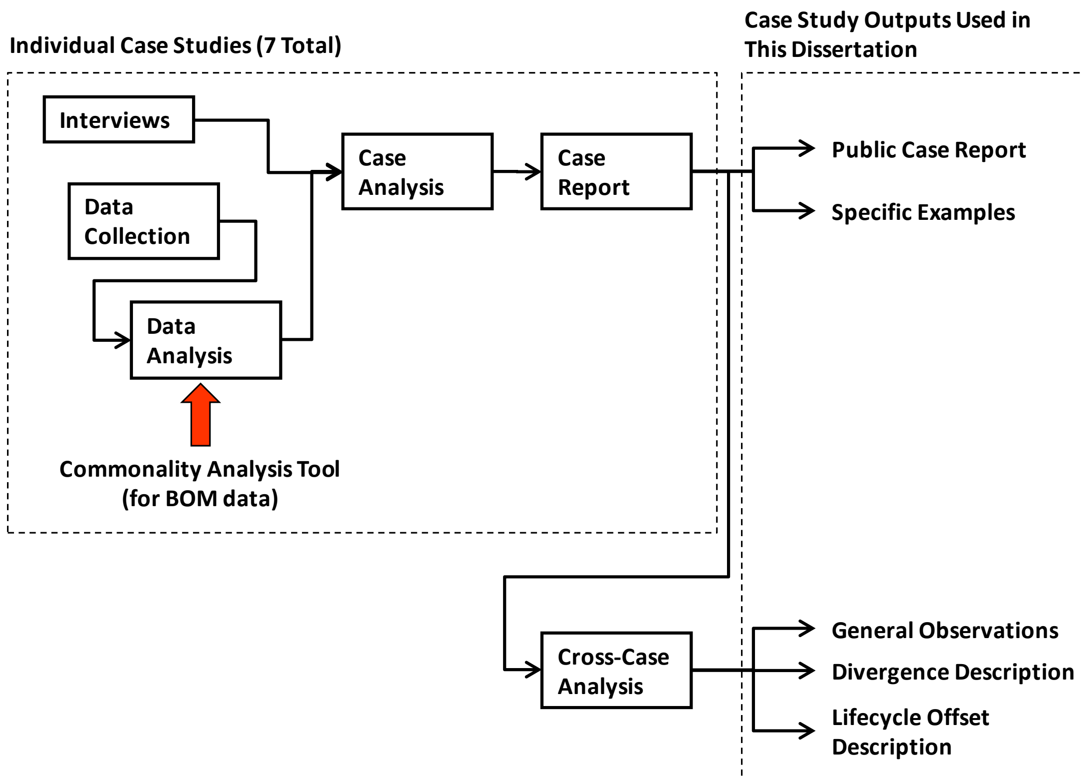


Figure 14: Basic process flow diagram for the field research portion of this dissertation. Data collection and analysis could not be conducted for all cases. The rightmost entries represent the case study outputs as utilized in later chapters of this document.

3.3. The Individual Case Studies

The individual case studies were a combination of interviews; data collection and analysis; and reporting; all of which were designed to better understand the development history of each complex product family from the perspective of commonality. While the individual cases were guided by the high level research questions, each case was unique in terms of the emphasis placed on each research question and the availability of information.

"Availability of information" refers to both the existence of information and the willingness of a given organization to share this information. Even though all case studies were conducted under Non-Disclosure Agreements, widely varying levels of willingness/ability to share information were encountered. An organization's hesitancy to share the requested information, which included product development investments and detailed breakdowns of individual product costs, was understandable as this information provides high level insights into a company's product development strategy, product development performance, and underlying cost structure.

Each individual case study entailed gaining executive level support for the study; working with a study contact to plan logistics, identify interview participants, and manage intellectual property concerns (e.g., Non-Disclosure Agreements); conducting on-site interviews and data collection; conducting follow-up data collection and processing; and reporting. Executive sponsorship was critical to "opening the doors" of each organization as visits from academic researchers are not overly common within product development organizations and may be viewed with concern.[15] Once a high level executive was convinced of the value of the study, the majority of this problem was resolved. After study approval, the active participation of the case study contact was required in order to gain access to the correct people and information and to obtain valuable feedback on the reports. The case study contact was absolutely critical to the success of each study.

Each case study involved one or several site visits that totaled approximately one week in duration. The main focus of each visit was on conducting interviews (typically between ten and twenty per company) with employees from a broad range of job descriptions and management levels. The interviews were typically conducted one-on-one and were one hour in duration.[16] Every attempt was made to interview employees in a broad range of leadership roles including program (and sometimes corporate) executives and managers from engineering, manufacturing, field operations, and business development. Individual contributors were also interviewed, especially in the context of investigating interesting avenues identified during the initially scheduled interviews with management. While employee roles and availability varied across the individual case studies, each study had the involvement of a broad spectrum of employees that was deemed to be critical for establishing a holistic view of commonality.

The interviews served several purposes. First, they provided individual accounts of the product family history based on individuals' experiences and their recollections. Second, the interviews provided multiple opinions on specific conceptual areas of interest such as divergence and lifecycle offsets. While the interviewees were generally in agreement with one another, considerable differences did exist in some cases, mostly due to differences in perspective rather than a strong discrepancy in the recollection of "facts." For example, differences arose several times in regard to definitions of commonality. Manufacturing employees, especially those associated with materials management, tend to focus on common part numbers (i.e., fit, form, and function compatible), while research and development employees focus more on common technology and process. Third, the interviews provided opportunities to identify new, case-specific areas of investigation as they emerged. For instance, several interviews were scheduled in order to perform a more in-depth analysis of a case-specific example that was not

[15] While collaboration between industry and academia is common, my personal observation is that much of this collaboration occurs between academia and the research arms of companies. Collaboration between academic researchers and actual product development programs seems to be less common based on my experiences with the case study participants.

[16] One company preferred a group format with presentations used to guide the discussion. This format limited the value of the interview time because of the presenter/audience format and the presenter's desire to "stay on track" with his or her presentation. While this style of interviews did produce useful results, some quality was sacrificed due to the rigidity of the structure and pre-planned content.

identified prior to the start of the site visit. Also, useful product information sources were sometimes identified during the interviews.

A semi-structured interview technique was utilized for the interviews. This technique recognizes the difficulty of, and potentially lost opportunities associated with, defining an interview script and then forcing the interview to follow this script. Each interviewee has a different set of experiences and expertise that is difficult to assess prior to the interview. Given this, it is extremely important to have a general plan for the interview and to provide general guidance during the interview, while at the same time having the flexibility to pursue fruitful avenues of discussion as they arise. The rationale for semi-structured techniques is discussed in many qualitative research references such as Stake (2006), Marshall & Rossman (2006), and Yin (2003). Marshall & Rossman sum up the rationale as follows: “The participant’s perspective on the phenomenon of interest should unfold as the participant views it (the emic perspective), not as the researcher views it (the etic perspective)” (Marshall & Rossman, 2006, p. 101). The Discussion Guide that was utilized as a starting point for the interviews is included in the Appendix, along with the Case Study Introduction. Both documents were distributed to each participant prior to their interview.

Prior to the site visit and associated interviews, requests were made for development program investment data and manufacturing cost data, with a strong emphasis placed on materials cost information, given the strong contribution of materials costs to total manufacturing costs in systems integrator operations such as those studied in this thesis. The investment data was requested in order to examine the extent to which development costs for the follow-on variants were lower than those of the lead variant. Overall development cost reductions were expected based on the reuse-driven development cost decreases that are often cited in the literature. Materials cost analysis was planned in order to identify common and unique components within a given product family, and therefore, to quantify the scope of the actual platform. Discussions with the case study contact quickly determined whether or not the requested data existed; whether or not the data quality was acceptable for further analysis; and whether or not the company was willing to provide this information.

As illustrated in the case study discussions, the quantitative data analysis portion of the study was partially successful. Several of the programs had data in a useful format and were willing to share this data. Several others had the data but were not willing to share it. Others did not have the data in a format that was usable for automated analysis. While all but two companies provided some degree of quantitative data, only two out of the seven companies provided both product development investment data and material cost (Bill of Material, “BOM”) information. When BOM cost data was made available, this data was analyzed using a custom-developed Commonality Analysis Tool that is described in the next section of this chapter. The analysis of available information was integrated into the respective case analyses and did not uncover any surprises in the way of contradictions between corporate data and employee recollections.

The main output of each individual case study was a confidential report that detailed the development history of a given product family based on the interviews and data analysis, where applicable. Each report followed a common structure: introduction; brief discussion of context; product family history presentation; observations from the case; and company-specific recommendations. Each company reviewed its own confidential report. This check helped to ensure factual correctness and provided each company with an opportunity to challenge my interpretation of the case facts, if the company believed that I had made an error. In the few cases of disagreement, the company was asked to provide additional relevant information in order to help correct the record. While the reports are believed to be factually correct, there are clearly multiple interpretations of these facts; varying degrees of emphasis that could have been placed on the observations; etc. That said, the high level observations within each case report could be easily repeated by another researcher studying the same program.

3.4. The Commonality Analysis Tool: Materials Cost Analysis for the Individual Cases

An analysis of part-level commonality is one method of analyzing the underlying platform within a family of products and changes in this platform over time. An automated tool was developed to perform this analysis on Bill of Material (BOM) data, when made available by the participating companies. The tool enables commonality between products to be examined at any given point in time and through time. The part-level analysis represents one view of a platform; a view that represents the actual collection of common parts in the end products. From this view, the platform represents a collection of components that are not necessarily connected to one another via mechanical interfaces, communications signals, etc.

The analysis tool examines two types of commonality in production: sharing and reuse. The "sharing" analysis examines the degree to which components are utilized by the various product family members at any given time, and the "reuse" analysis, examines the degree to which previously developed components are carried forward to new products (Figure 15). In terms of the five class framework in Chapter 2 and a two product family, the sharing analysis distinguishes between outcomes that are Unique to A (Class 1 and Class 2 components), Unique to B (Class 5 components), and common (Class 3 and Class 4 components) at each point in time. In other words, the Commonality Analysis Tool provides information about design outcomes, but not design intent.

Two types of reuse are considered in the analysis. First, reuse can occur between generations of a given product model. Second, reuse can occur when previously developed components are selected from other product models. The analysis separates the two types of reuse sources but groups all non-generational reuse into a single "from other products" source. This approach simplifies computational complexity and results presentation. The approach does not represent a fundamental limitation of the analysis algorithm.

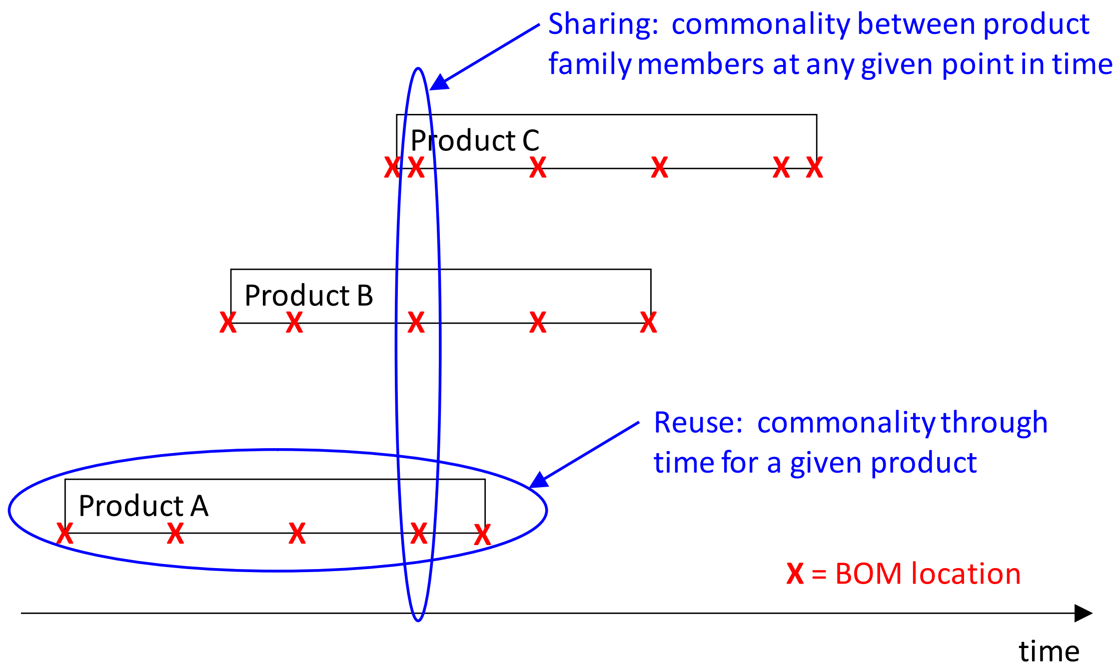


Figure 15: Sharing and reuse within a product family.

The Commonality Analysis Tool process flow is illustrated in Figure 16 and is described as follows. There are two main inputs to the analysis tool. The first input is a product family history file that is a matrix with product models and time steps as the respective columns and rows. The second input is a separate indented Bill of Material (BOM) file corresponding to each entry in the product family history matrix. The combination of the history file and group of BOM files defines the product family history from the perspective of parts. After loading inputs, the next step in the process consists of identifying the "leaves," or all the parts in a given BOM hierarchy that do not have dependent children (Figure 17), and processing these leaves for later analysis. Once identified, the leaves list is sorted and quantities are combined for each unique[17] part number. The result is a parts list that has one line item for each unique part number. After leaf computation, an optional filtering step can be completed in order to remove low and zero cost components such as fasteners, electrical components, and procedures. This filter can be used if the available cost data has significant errors and the decision is made to count part numbers or part quantities. The filtered or unfiltered leaves represent a flat list without hierarchy and are the basis for the remainder of the analysis.

[17] Here, "unique" refers to different part numbers, rather than to a part that is not common between two or more products.

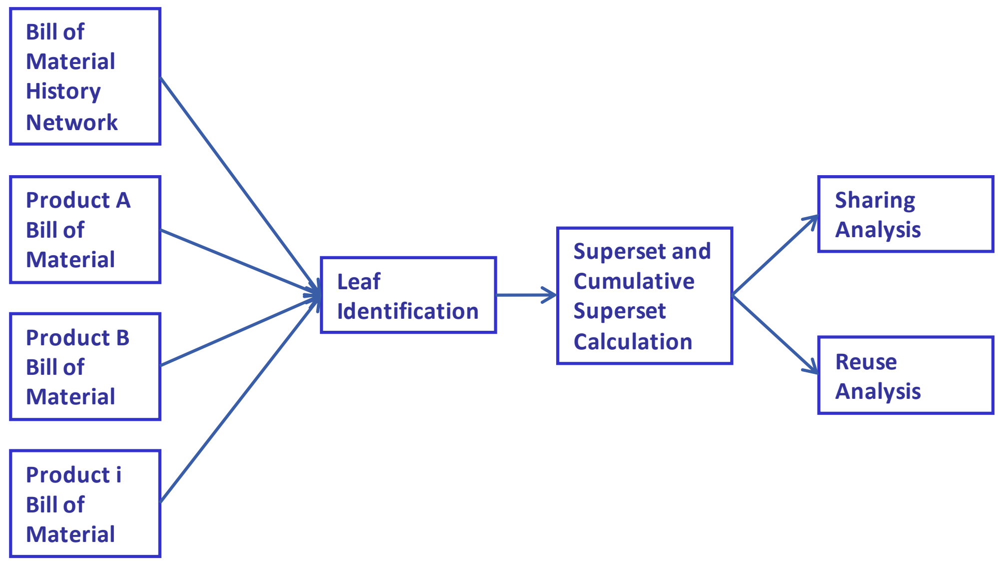
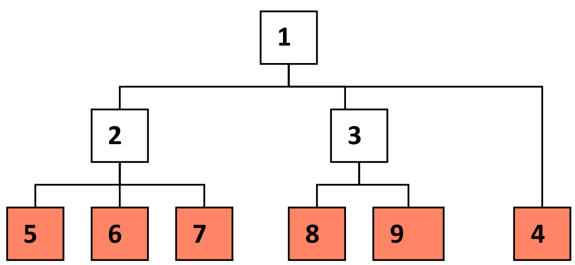


Figure 16: Basic process flow for the Commonality Analysis Tool. The Product Bill of Material boxes (left hand side) consist of multiple BOM's representing the time history for a given product, as illustrated in Figure 15.



BOM Level	Part Number	Cost	Leaf?
0	1	44	
1	2	19	
2	5	1	Leaf
2	6	8	Leaf
2	7	10	Leaf
1	3	19	
2	8	15	Leaf
2	9	4	Leaf
1	4	6	Leaf

Figure 17: Two views of Bill of Material leaves, or lowest level parts. The left hand view shows a visual depiction of the hierarchical structure of an indented BOM, along with highlighted leaves. The numbers in the boxes represent part numbers. Note that Part 4 is a leaf and is only at Level 1 (the root node; Part 1 is at Level 0). All other leaves are at Level 2. The right hand view shows a spreadsheet that includes part costs. Leaves are marked. If desired, the marked leaves can then be filtered based on a cost threshold (e.g., remove leaves that cost less than $5).

After computation of the leaves, two types of "superset" calculations are performed at each time period in the product family history. The first calculation output, called the "superset," refers to the total set of parts utilized by the members of a product family at a specific point in time. The superset represents the union of all active BOM leaves. The calculation of the superset at any given time has no relationship to other time periods. In addition to the calculation of the superset at any given time period, the cumulative superset is also calculated. The "cumulative superset" represents the superset of unique part numbers utilized from the initial time period of the analysis to the current time period of analysis; i.e., it is the superset of all prior and current supersets. Given this relationship, the size of the cumulative superset is a non-decreasing function of time. The superset may increase or decrease with time.

While the superset and cumulative superset are required for calculation of commonality levels, they provide useful information in their own right. The superset represents a measure of the component complexity that an organization is managing at any given time. Increases in the number of components may contribute to increases in overall complexity. The cumulative superset can be thought of as a measure of the total historical development scope of a given company's operations with respect to a given product family. The cumulative superset is likely correlated to total investment in the product family history, although this hypothesis would need to be investigated through further research.

After the previous calculations are made, the analysis splits into either the analysis of reuse or sharing within the product family. The reuse algorithm calculates reuse from prior model generations and tracks the sources of this reuse. At each time period, the algorithm analyzes the current BOM for parts present in prior BOM's from the same product model, then searches for parts from the prior cumulative superset, then allocates any remainder as new development. As a simple example, Figure 18 illustrates a reuse test case calculation. Three generations of the same product model (referred to as products A1, A2, and A3) are illustrated along the horizontal axis with the number of unique part numbers depicted on the vertical axis. Product A1 is all new development, hence the single blue bar. Product A2, the second generation of the product, reuses a portion of the initial product (blue bar, middle column), while also replacing several parts with new development (red bar on top of middle blue bar). The same process occurs with Product A3: a reduced number of the original Product A1 parts are utilized (blue bar, right column); Product A2 parts are carried forward (red bar, right column); and new Product A3 parts are introduced (green bar, right column). This same calculation is easily repeated for the dollar value of the parts and also for part quantities.

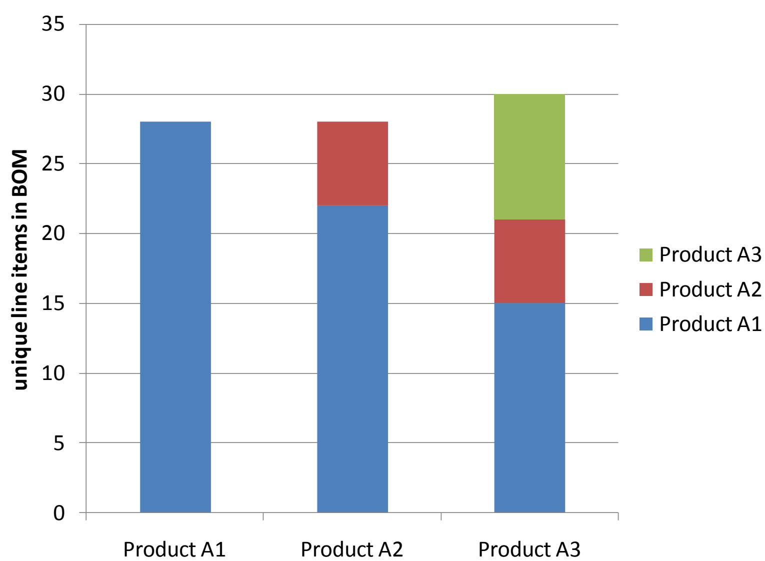


Figure 18: Example of a reuse calculation for three product versions that represent generational improvements. New generation products (e.g., products A2 and A3) may reuse components from prior generations and may also introduce new components, some of which are additions, others of which are replacements.

The reuse analysis provides two potential insights. First, the degree of change in the product line is clearly visible. Reduced degrees of change represent stability. This is not to say that stability is an end goal, as stability may be a direct impediment to innovation. Second, in the case of multiple products the degree of reuse between different product lines can be determined. The reduced development scope associated with reuse is an often-claimed benefit of commonality. The reuse analysis can also indicate information about the presence of learning curve benefits since reuse leverages historical production.[18] An analysis of reuse does not provide any indication about economies of scale, as economies of scale require the examination of commonality between models at a given point in time; i.e., an analysis of "sharing."

The sharing analysis represents the part-level view of commonality that is directly linked to shared economies of scale in production. The sharing analysis is relatively simple. For each time period, the intersection of the superset of unique items and each active BOM is calculated. In this manner, the varying levels of commonality are computed. For example, given a three-product family with product names "A," "B," and "C", three intersections are performed and seven potential commonality classifications result: "ABC," "AB," "AC," "BC," "A," "B," and "C." Class "ABC" is common to all three products; classes "AB," "AC," and "BC" are common to two products; and classes "A," "B," and "C" are unique to one product. The complexity of the classification scheme increases with increasing number of products. A three-product analysis example is illustrated in Figure 19. Note the decreasing commonality levels and increasing uniqueness with time. The trend illustrated in Figure 19 is indicative of the divergence trend that was observed in practice and that is discussed in depth in Chapter 5.

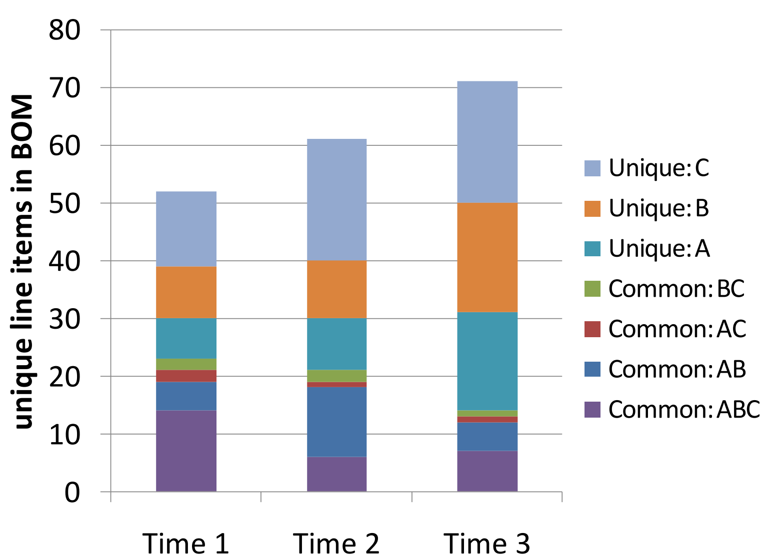


Figure 19: Sharing calculation for a three-product family (products A, B, and C) analyzed at three different time periods. Notice the increasing uniqueness (span of the top three segments of each column) with time, indicating the presence of divergence. Note that the Commonality Analysis Tool examines outcomes and is unable to examine design intent.

[18] Future work could examine part cost trends in an effort to determine the degree of the learning benefit.

The outputs of the Commonality Analysis Tool may provide additional insights into the degree of commonality within a product family and the evolution of commonality over time; however, several weaknesses in the tool and approach mean that the outputs represent an additional piece of information rather than a definitive assessment. First, the automated analysis cannot check degrees of similarity between individual parts even though similarity may have significant development, production, and operations benefits.[19] This limitation is driven by the need to make automated comparisons of unique part numbers. Any fit, form, or function change to a part requires the assignment of a new part number and even though a change may be minor, the current algorithm treats the modified part as completely unique. The result is the computation of a lower bound on commonality and an upper bound on uniqueness. Overcoming this limitation would require expert "tagging" of parts based on rules for similarity or on the creation of an automated analysis tool that has the capability to detect similarity, a difficult challenge at best. Second, the analysis tool in its current form examines the leaves of a given product BOM, ignoring potential commonality at higher levels of the assembly hierarchy even though commonality at higher levels could yield increased benefits (Figure 20). This limitation could be overcome through implementation of a cluster analysis algorithm. Third, the analysis tool examines relatively mature product designs (e.g., that have a BOM) and does not explore conceptual development, the stage at which rates of divergence are likely to be the highest. Improvement of the analysis tool is left to future work.

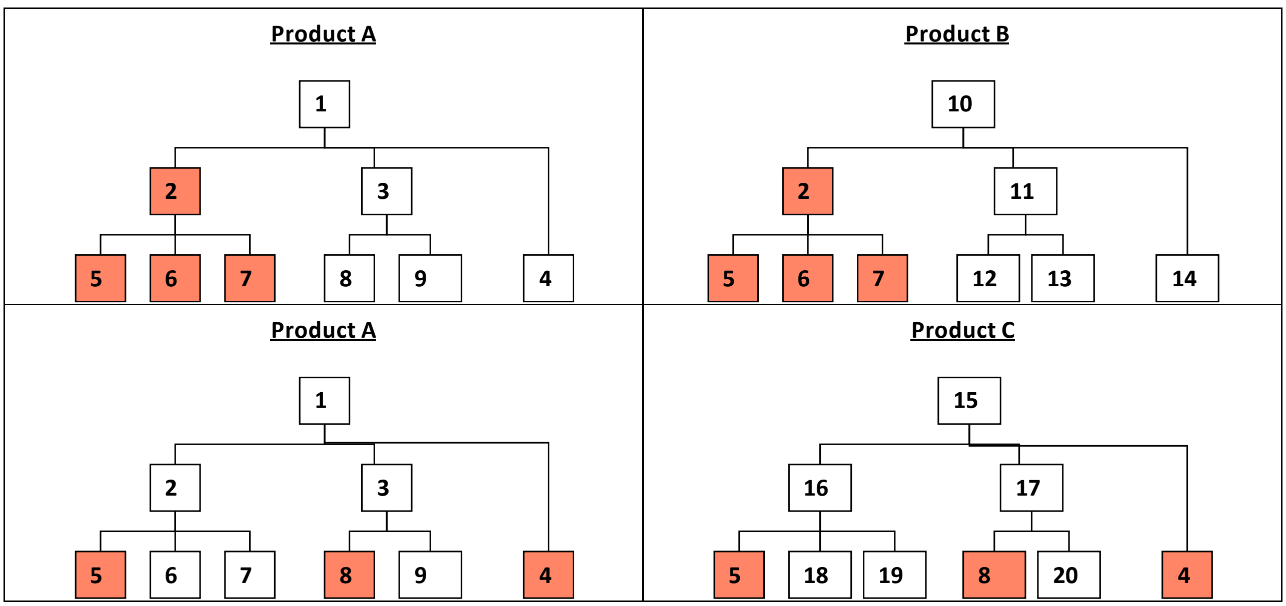


Figure 20: Clustering is ignored by the initial model implementation yet likely an important factor in connecting automated analysis with the true benefits and penalties of commonality. The top row of this figure illustrates a common module ("2") that is shared by products A and B. This module consists of parts 5, 6, and 7. The second row of the figure illustrates part-level commonality with parts 4, 5, and 8 being shared between products A and C. The shared module (top row) is likely to realize increased economies of scale in production and decreased development costs in comparison to the dispersed common parts (bottom row). The current analysis algorithm only detects the leaves in both cases and does not differentiate between the two.

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[19] The algorithm examines assembly similarity by decomposing these assemblies into common and unique elements, but the algorithm cannot decompose and analyze inseparable parts (the leaves of the BOM).

3.5. The Cross-Case Analysis

After completion of the individual case study reports, a cross-case analysis was conducted to glean insights with respect to the main case study questions. The cross-case analysis entailed multiple readings of the final individual reports and the use of an affinity process to tease out the key case study findings. Replication of the same finding across multiple cases forms the basis for a cross-case finding. In some instances, contradictory case findings were identified. These contradictions presented the opportunity to increase the explanatory power of a given observation through contrast and through limiting the generality of the given observation (Yin, 2003).

As an example of theoretical replication, or the identification of explainable, contradictory information (Yin, 2003), consider the observation that formal management controls appeared to be linked to an organization's ability to pursue common development and to manage commonality throughout the lifecycle. For all but one of the seven studies, there seemed to be a link between the presence of formal organizational controls and the ability to pursue commonality: the presence of a platform manager or management team led to consideration of commonality and also helped to drive cultural changes. Lack of this leadership resulted in independent development. One case, that of the military aircraft family, provided a seemingly contradictory finding. Awareness of the need to consider commonality was pervasive throughout the organization, but barely present in the organization's formal structure. While process controls existed, they were utilized more as a final quality check than as a driver of behavior. My initial view was that companies progress toward increasingly formal managerial control of commonality as they improve their ability to leverage commonality as a tool. Based on the contradictory information identified in the military aircraft case, my view was modified to a more complex and potentially more accurate view. The first level of commonality implementation is naive: no formal controls exist for commonality and there is little awareness of commonality within the organization. The second level is the presence of formal controls including organizational structure and processes and some degree of cultural awareness. A third, elevated level is the de-emphasis of strong organizational and process controls due to the existence of a pervasive culture that examines commonality decisions by default. In this third level, commonality appears to have taken its place as one of many aspects that should be considered during the development of product families. In the second stage, commonality may have been overemphasized as a way to effect a corporate change.

3.6. Limitations of the Field Research

The field research design had several limitations that must recognized. First, the case study method provides replication logic rather than statistical sampling. While prevalence of an observation within the seven cases suggests that the trend may likely be generalized to other complex product families, the seven cases cannot be claimed to be a statistical representation of the potential population of complex product families. If statistical sampling had been a research goal, a method such as a survey would have been a much better approach (Yin, 2003). Second, the multiple-case approach required extensive amounts of time and reduced the time that could be invested in any one case study. Breadth of observation was pursued at the expense of depth. Third, while every attempt was made to design and conduct the case studies in an unbiased manner, complete elimination of bias was impossible to achieve. My interests as a researcher combined with my prior experience in complex product development influenced my interview questions and data search.

In addition to design limitations, the study faced several implementation challenges. First, product data availability was more limited than had initially been thought; limiting the ability to quantify commonality levels and their changes over time. Second, use of Non-Disclosure Agreements provided excellent access to information (less the data limitations) but created challenges in terms of public reporting of this information. The decision to conduct the studies within the confines of Non-Disclosure Agreements was a conscious research decision. By having nearly full access to information, I was able to better understand the full “story,” which then had to be filtered for public release. The alternative of not signing Non-Disclosure Agreements would have been rejected studies due to confidentiality concerns and, in cases that were allowed to proceed without the use of a Non-Disclosure Agreement, to more abstract discussions about the programs. The latter outcome would have entailed creating generalized observations from abstract discussions about each case and in so doing would have reduced the quality of this research. Third, while the core desired information concerned divergence and lifecycle offsets, these two topics did not, and could not, serve as the core discussion topics. Initial informal discussions with industry experts indicated that I would need to examine the program histories and their contexts and then extract information about divergence and lifecycle offsets. In other words, an understanding of the topics would need to be teased out from information familiar to the interviewees, as opposed to asking the interviewees to provide the findings. The need to approach the research in this manner required a broader study scope. As a result, a wealth of useful, but tangentially related information was collected. Much of this information has not been reported in this dissertation as it is off-topic, but some of the key points have been included in the hopes that they will prove valuable to future programs that are considering commonality and to the academic research community.

3.7. Chapter Summary

The research methods and Commonality Analysis Tool described in this chapter represent the foundations of the case study portion of this research. The mixed method, multiple case study design targeted breadth of observation and learning. The Commonality Analysis tool was designed to support further depth of analysis, when quantitative data was available. The methods and tool described in this chapter were applied to the seven case studies as reported in the following chapter and in the Appendix.

4. The Case Studies: Insights into the Realities of Platform Development Practice

4.1. Introduction

Seven case studies of complex product families were conducted in order to better understand platform development practice. The cases are listed in Table 3 and span across the aerospace, automotive, and high technology sectors. All but one of the cases (the military aircraft case) were of commercial product families. The types of cases were intentionally selected from a broad range of industries in order to ensure a diverse range of contexts from which to draw a better understanding of the realities of industrial practice; in particular, the realities of divergence and lifecycle offsets and their influence on the benefits and penalties of commonality. The diversity of the cases was expected to provide insights of increased generality compared to those insights that would have been gleaned from a tightly focused study of multiple product families within one industry.

Table 3: The seven cases cover a broad range of industries.

Designation	Product Family Type
Case A	Automotive
Case B	Military Aircraft
Case C	Commercial Aircraft
Case D	Business Jets
Case E	Printing Presses (Commercial)
Case F	Communications Satellites
Case G	Semiconductor Manufacturing Equipment

The participating companies are publicly traded and well-respected in their given industries. All but one company, the military aircraft company, has chosen to remain anonymous. The military aircraft case (Lockheed Martin Corporation's F-35 Joint Strike Fighter program) would have been nearly impossible to disguise in a manner that would have still enabled findings about commonality to have been reported. For the other companies, anonymity was easier to preserve due to the existence of larger numbers of competitors. Although the anonymity required to protect corporate identities has required the removal of company and product specific identifying information, the anonymity does not significantly detract from the findings of the cases.

Successful programs (as evidenced by market performance) were selected, with the assumption being that platform-based development best practices could be gleaned from these successful programs. Studying failed attempts at developing complex product families would also produce valuable information with respect to platform-based development, although studying failures is likely to have practical issues of access. The study of failed platform-based development efforts is left to future work.

In addition to covering a breadth of industries, the cases were diverse in terms of their production rates, product costs, and development investments. The cases had a significant range in annual (or expected annual) production rates, ranging from satellites that are produced in quantities of several units per year to automotive families that are often produced in quantities of greater than 100,000 units per year. Likewise, product prices had a significant range, ranging from a typical automobile price of greater than $20,000 (2008 dollars) to the price of a satellite or military aircraft both of which exceed $100 million (2008 dollars). For the most part, the cases examined the "middle" of a product spectrum that ranges from multi-billion dollar, one-off (or nearly one-off) systems, such as oil production platforms, to much lower priced consumer products that may be produced in the millions. (Refer to Figure 21.) The closest studied example of a low volume, high dollar product is the communications satellite case. The automotive product family is the closest case to a consumer product, although a vehicle probably represents the most expensive product that is purchased by a typical consumer. The remaining five cases loosely cover the gap between the two. The development costs for the case study products range from millions to billions of dollars, although these numbers are difficult to obtain publicly and the companies are highly sensitive to their disclosure. Development costs vary by over three orders of magnitude.

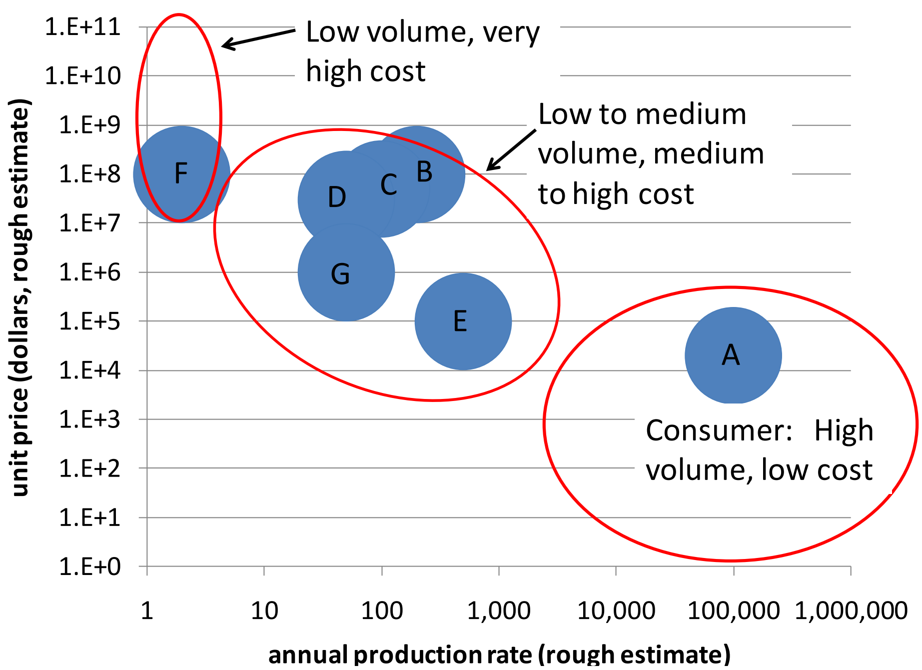

Figure 21: Very rough indications of the annual production rates and unit prices for the case study product families. In order to protect the case identities, the indicated data points are typical of products in the industry rather than an exact indication of the case product's data.

The product families were in different lifecycle phases, ranging from products that were not yet in full production (military aircraft, automotive) to mature product families (e.g., both the business jet and commercial aircraft programs). The military aircraft program and automotive programs were the only programs that did not have significant production volumes across all planned variants at the time of the case study. The remaining five product families (commercial aircraft, business jets, printing presses, communications satellites, and semiconductor manufacturing equipment) had significant production for all planned variants (that were acknowledged by the company at the time of the study). These families also had product family members that were no longer in production, but were still in operations.

Table 4 provides a brief summary of the seven case studies, including their product type; the number of product family members considered; illustrative production rates and product prices; and the case study focus. Two of the seven case studies (cases A and B) were investigations of recent, development efforts aimed at producing a small and specific set of near term products. The remaining five studies were of a larger number of products created over longer time periods. The product histories of these five studies involved the creation of initial product family plans; the development of all or a portion of the planned variants; and then the follow-on development of variants that had not been part of the original product family plan. The field research portion of the studies entailed conducting 119 interviews, typically lasting one hour, over the course of 32 days spent at the seven participating companies. Quantitative data related to commonality (either metrics or product bill of material data) was collected to some degree for four of the seven cases. Product development investments were made available by three of the participants.

Table 4: High level case summary. Inexact nature of the data required to protect case anonymity. The intent is to provide order of magnitude information that highlights the breadth of the seven cases.

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Product Type	Automotive	Military Aircraft	Commercial Aircraft	Business Jets	Printing Presses	Communications Satellites	Semiconductor Manufacturing Equipment
Number of Products in Family	2 main product lines, many options within each	3	5+ (evolving number of models)	4+ (evolving number of models)	3 product lines, 10+ models over history	10+	3 product lines, 15+ models over history
Typical Annual Production Rates for Products in this Industry	100,000+	200 (approximate plan for this product)	100+	50+	100+	1+	50+
Indicative Product Price	$20k+	$100M+	$50M+	$30M+	$100k+	$100M+	$1M+
Study Focus	Development of two models with a proactive approach to enabling commonality	Development of three models with a proactive approach to enabling commonality	Commonality within the historical evolution of product models	Commonality within the historical evolution of product models	Commonality within the historical evolution of product models	Commonality within the historical evolution of product models	Commonality within the historical evolution of product models; more recent proactive approaches to developing multiple models

While the case studies had a focused intent, the study outcomes varied due to factors such as corporate culture, information availability, and information access. For example, one of the aircraft companies placed a strong emphasis on process and tended to guide discussions in this direction. The end result has been a rich collection of information that does not fit neatly into a boiler plate template.

The original confidential reports and the public versions presented in this dissertation followed a consistent format but did not “force fit” results into a specific examination of divergence and lifecycle offsets in the context of the benefits and penalties of commonality: this task was left to the cross-case analysis. The individual case study report observations covered the most prominent points of each study, as evidenced by repeated observation in the interviews and any supplied documentation. Many of the results were well-matched to the study topics given the initial goals of the study and the guiding themes of the semi-structured interviews; however, the flexible approach to reporting enabled the reporting of critical insights that may have been passed over had a rigid framework been established prior to the field work.

The public versions of all seven case reports are included either in this chapter or in the Appendix. The Case A (automotive family) and Case B (military aircraft family) reports are included in this chapter as examples that provide excellent insights into the development of platform-based product families and the impacts of divergence and lifecycle offsets. These companies faced similar challenges associated with divergence and lifecycle offsets even though they have significantly different prices and production rates and come from different industrial sectors. The full Case A and Case B reports are also included in the main body of this dissertation in order to expose the reader to the rich context from which case study findings are derived. Much of this context is lost when the case findings are abstracted to more general findings; i.e., to cross-case findings. Very brief overviews of the remaining five reports follow the Case A and Case B reports. The full public reports for Cases C through G are included in the Appendix and the reader is encouraged to review these reports in order to gain additional exposure to the realities of platform development efforts in the context of complex products. Each case offers useful insights. Only the highlights have been addressed in the main body of this dissertation.

Following the case reports (Cases A and B) and case report summaries (Cases C through G) is a discussion of the cross-case findings from all seven cases. The discussion of the overall findings is then followed by deeper examinations of divergence (Chapter 5) and lifecycle offsets (Chapter 6).

The lettering convention utilized in the following summaries is applied to the case, product family, company, and program naming conventions. For example, Case A represents Product Family A which was developed by Company A during Program A.

4.2. Case A: Automotive Product Family

The automotive industry is fiercely competitive. While automobile development and manufacturing is a capitally intensive business, this intensity is not an insurmountable barrier to entry as demonstrated by the large number of capable competitors. The presence of strong and growing competition across all segments of the industry has driven profits down and created uncertainty in terms of future market share expectations. The resulting thin margins and market uncertainty have created a strong focus on all aspects of cost reduction. Platform-based development represents one of many approaches that auto companies are pursuing in an effort to reduce development cost, lead time, and risk.

Manufacturing within the industry is characterized by high production rates (>100,000 units/year in many cases) and high capital intensity, both of which guide and constrain product development decisions. The high production rates drive an intense focus on recurring cost as small cost changes over a large number of units are significant. The high production rates drive the need for expensive infrastructure that supports mass production. The large capital expenditure associated with a new manufacturing facility may exceed $1 billion, creating strong incentives for continual reuse and modification of existing infrastructure.

Case A consists of a platform-based automotive product family development program that primarily involved the development of an SUV and truck, along with an underlying platform that consisted of shared underbody elements such as chassis structures, suspension, powertrains, steering, and brakes. The SUV was developed first, with the truck following by approximately two years. The truck production rate was expected to be about twice the rate of SUV production.

Company A is currently moving from an independent product development approach toward a platform-based development strategy as a way to better align product development decisions with overall corporate profitability goals. Development has traditionally focused on the development and manufacture of individual vehicles with overall profit and loss responsibility for each vehicle being held by an individual program manager. The culture has traditionally mimicked the organization structure with the focus being on single vehicle lines as opposed to larger groups of related vehicles. The result of the historical culture and organization structure has been a strong focus on individual products, resulting in attempts at local optimization at the potential expense of overall corporate profitability. Case A represents an attempt at cultural and organizational change.

4.2.1. Brief History

Context

Program A represents an attempt by Company A to bring two previously common products back into alignment after they had diverged. The original SUV was a new market entry into the sport utility "whitespace," effectively serving as both a market test and market shaping force. In order to minimize development expenditures and leverage economies of scale, Company A based the original product on its existing truck platform, making minimal modifications. A high degree of commonality existed with required exceptions being mainly in sheet metal (i.e., the SUV body) and interiors. The truck team developed the SUV, ensuring proper knowledge transfer, awareness of previous design rationales, and strong incentives for maintaining commonality. The result was the efficient creation of an SUV that shared many characteristics with the truck line. The resulting product was very successful in the market.

SUV market success (sales volumes and profits) led to a decision to split the SUV and truck vehicle lines and an attempt to further optimize the SUV design with respect to the SUV market needs. High sales volumes combined with high profit margins made moves away from commonality acceptable and in many cases, probably the correct approach. As an example, a new rear suspension was introduced to the SUV in order to improve ride quality. The optimization decisions made sense from the business side and led the vehicle designs away from commonality. The success of both vehicle lines created little incentive to compromise for the sake of commonality.

Future versions of the SUV achieved reduced market success and as a result, the uniqueness between the SUV and truck products was reexamined. A platform-based development program was initiated to replace both product lines.

Platform Vision

Key executives at Company A had a strong belief that standardization of parts, processes, and architectures was at least partially responsible for the success of Company A's competitors and that the pursuit of commonality was critically important to Company A's future success. One outcome of the strong executive interest in commonality was Program A which consisted of two major thrusts. The first was the development of new models for three of Company A's major vehicle lines, with high levels of commonality planned between the two vehicle lines reported in this summary. Commonality would be leveraged to the maximum extent possible without compromising value, quality, or brand differentiation. The second thrust of the program was focused on changing the organizational and cultural aspects that were driving independent product development and the cost challenges associated with this strategy.

From the standpoint of product development, Program A was expected to provide many benefits: reduced total product development cost (including testing); shortened product development cycle times; reduced manufacturing costs; and improved quality. The program initially estimated an acceptable internal rate of return; reduction in the number of prototypes by about 40%; reduction in lifetime headcount by approximately 20%; and a significant direct manufacturing cost savings. Non-recurring benefits would be achieved through a reduced total development workload, while recurring benefits would be linked primarily to shared economies of scale savings associated with the extremely high production rates of the SUV and truck lines. The SUV would realize higher shared economy of scale benefits on a per vehicle basis, since the SUV was expected to have roughly half the production volume of the truck. When comparing common parts to the independent alternatives that these common parts would potentially replace, the SUV would experience a larger relative cost decrease when compared to the relative cost decrease expected by the truck program.

Given that the customer benefits of commonality were indirect at best, commonality was to be carefully managed to ensure minimal impact on revenues due to potentially reduced vehicle performance and customer perception of vehicle uniqueness. Commonality was also expected to create higher degrees of stability in common parts due to strong managerial controls placed on common parts. Through careful consideration of the needs of the two vehicle lines, common components would be designed once, and then be utilized by each vehicle program.

The scope of commonality was to be broad and was classified into three major categories: common components; common manufacturing processes; and common architecture. The different types of commonality would provide varying degrees and types of benefits, although achieving commonality at the component level also represented the achievement of common process and common architecture.[20] Component commonality would eliminate redundant development and testing and enable common manufacturing processes: component commonality was believed to represent the best case from the standpoint of cost control, although cost control obviously had to be balanced against the potential negative impacts on revenue. If component commonality could not be achieved, process commonality and architecture commonality represented two alternatives. The former would at least partially enable suppliers to operate mixed model manufacturing lines and potentially enable mixed model manufacturing on Company A's final assembly lines. The latter type of commonality, architectural commonality, offered the least tangible benefits, although conceptual reuse clearly was better than starting from a clean sheet of paper.

In addition to the actual vehicle program deliverables, Program A was intended to trigger a cultural and organizational shift that would expand product development thinking and actions beyond the individual vehicle level. The existing organization strongly supported the single vehicle culture, with the majority of decision authority resting with the program managers, each of whom was responsible for the profit of a given vehicle line. While program managers were certainly well-intentioned from the perspective of improving Company A's overall business, their incentives for doing so were based on maximizing the profit of their individual vehicle line and meeting their customers' needs. A program manager charged with a single vehicle model could not be expected to voluntarily make a decision that would negatively impact his or her program, even if it provided a net benefit to Company A. Program A intended to counteract this culture by making cross-vehicle level decisions a requirement.

The organizational and cultural shift began with the creation of a new platform manager role. The platform manager would serve as the owner of all common development and would work with the program managers to develop optimal solutions. Final decision making authority on common parts and processes would rest with the platform manager, and any decision that was challenged by a vehicle program manager, would be taken to the Vice President level for resolution. Each program manager would continue to be responsible for the profitability of his or her product line. While the split seemed straightforward at the onset of the program, challenges arose relating to the platform team's ownership of vehicle parts without ownership of vehicle attributes (e.g., performance).

The platform team established and communicated a clear plan for commonality; created management processes associated with common parts and processes; and began to demonstrate the different mindset required to make product development decisions across a set of products rather than within one product. The team illustrated the expected benefits and

[20] In the context of Company A, architectural commonality appeared to be synonymous with similar conceptual designs at the vehicle, module, and part levels. Architectural commonality translated into similar rather than common elements and discussions of architectural commonality typically referred to modules and parts.

penalties of commonality and, as needed, enforced rigorous control of commonality as the new culture began to take root. Examples of expected benefits were the previously mentioned development and manufacturing cost savings. An example of a potential penalty was a negative impact to performance and the associated decline in revenue.

A formal process was established for vetting changes to common components. Joint platform and vehicle program change control meetings ensured that changes to common parts did not slip through an individual vehicle program review without the proper consideration of the cross-program impacts. Additionally, cost adders associated with a given change that were above a certain threshold were reviewed during a high level program meeting.

In terms of program execution, the execution plan called for the introduction of the SUV with the truck following approximately 2 years later. Both vehicle teams would be heavily involved in the decision making process for the common components, processes, and architectures; a process that would be led by the platform team in order to ensure proper decision making from the perspective of Company A's overall profitability. Given that the SUV program represented the lead vehicle, the common development work on Intended Common components would be conducted in parallel with the SUV model.

Overall, the platform vision appears to have been well-developed and communicated. Specific opportunities for commonality had been identified. New low risk technologies and module concepts had been identified and rolled into the program plan. A strong leadership team had been put in place. Change management processes were developed and communicated. An initial analysis of the benefits and penalties of commonality had been conducted and translated into program metrics such as internal rate of return, investment (including headcount), and variable cost. The entire program had the strong support of executive management. The program was well-positioned to succeed.

Development of the SUV and Underlying Platform

Development of the SUV and platform was initiated after creation of the product family plan. After initial work had been completed on the designs of the SUV and underlying platform, Company A's Board of Directors reviewed and approved the SUV program, effectively locking in many high level platform decisions. After the program commitment had been made to the Board, the program moved forward at an aggressive pace: commitments had been made; needs were well-defined; and the schedule was extremely tight.

While the SUV team was working against a tight schedule, the truck program was scheduled to follow approximately two years later. The truck team was focused on more immediate programs, and did not have significant staffing for the future truck program associated with the Program A platform. Minimal staffing and a reduced emphasis significantly limited the truck team's ability to influence development decisions for Intended Common components, processes, and architectures.

Throughout the early phases of Program A, Company A was making compromises that would negatively impact its high volume truck; some knowingly and some unknowingly. Examples of compromises include the cost and weight of a common brake design; frame design constraints on front-end styling; and overall weight growth. These compromises were driven in part by the truck team's inability to bring full-blown technical analyses to trade study discussions: professional judgment was often all that was available to support truck design positions and was not enough to counterbalance the detailed trade studies provided by the SUV team. The imbalance in the level of design definition during platform trades resulted in platform decisions that were skewed toward the immediate needs of the lead variant (SUV), often at the expense of the follow-on variant. From the perspective of the platform team, the truck program had more time and, therefore, could accept greater design constraints. Platform development proceeded under the premise that SUV-related development would directly carry over to the truck program at a future date.

At the executive level, a strong hold was maintained on intended commonality during SUV development. Planned commonality was well-communicated and rigidly held on to, as anything less would have resulted in the loss of commonality through the course of the program. Doing so was relatively straightforward given the lack of truck program engagement and the resulting lack of an effective tension between SUV and truck design needs: while the needs of both vehicle lines were considered, decisions were weighted toward the needs of the SUV line. The strong hold on commonality likely produced suboptimal design compromises that later led to truck-induced divergence.

When the platform elements were "finished," Company A's development organization went back to business as usual. The platform manager was promoted to a new role and the entire platform team was dissolved. The SUV designs were relatively stable at that time and were moving towards the start of production. The truck team, on the other hand, was just beginning to ramp development of its new platform-based variant. At the end of the formal platform development effort, the platform team's expectation was that the truck team would directly carry over the established platform elements to its new model. The end result was different.

Truck Development, SUV Production

The SUV team was working hard to stabilize its designs in preparation for production. The team had worked through its conceptual development phase and had arrived at acceptable designs, including those associated with the Intended Common components. SUV design changes were now limited to addressing the results of the ongoing test program, with changes being made to address missed performance attributes and unsatisfactory safety test results.

While the SUV team was stabilizing its vehicle design, the truck program was just starting to ramp-up. The two year time separation between the two programs found the truck team facing a significantly different environment than the SUV team had faced during its development phase. First, cost pressures had increased. Second, the truck team was left to use Intended Common components that had been developed under the strong influence of the SUV team and limited truck team involvement. The Intended Common designs sometimes presented performance and cost compromises that became clear to the truck team as it worked through its product development cycle. Changing an Intended Common component to meet truck needs invariably meant that commonality would be lost: the SUV team was readying for production and had little incentive to accept new changes that could introduce risk to the start of production or to warranty costs. Third, the platform leadership team was gone; meaning the once active evaluation and control of commonality was basically nonexistent. The management of commonality was now left to the functional engineering managers who had a lower level of design influence than the program managers. The result of the above factors was a development environment that was ripe for the reduction of commonality with time.

Additionally, the incentives for pursuing commonality were different for the truck program, which had little to gain in terms of shared economies of scale because of already high volumes that reached areas of diminishing returns. The limited shared economies of scale benefits for the truck meant that there was little scale offset for a part that had more capability than required. Given the cost pressure, the truck team had strong incentives to fund new development work in order to produce a more optimal design that would have a lower variable cost than the Intended Common predecessor.

The Intended Common parts represented a dilemma for the truck team: the Intended Common parts sometimes represented design compromises that no longer fit within the new constraints imposed upon the truck team. Given the production status of the SUV program, the only option the truck team had for maintaining commonality was to directly carry over the Intended Common components. While making modifications to the Intended Common part in order to meet truck requirements was certainly an option, this approach would result in a loss of commonality given that the SUV was rapidly approaching production and was very limited in terms of the scope of changes it could accept.

The truck team was left with three options when an Intended Common part conflict arose: accept the performance penalty along with the resulting cost or revenue impact of an existing common part; create a new unique design that better met the needs of the truck program; or create a New Intended Common part that would suit the needs of both the truck and future SUV models. The first option, reuse of the existing Intended Common components, would result in decreased truck development expenses, time, and risk but could also negatively impact revenue and variable costs. The second option, new unique part development, would incur development expenses, time, and risk in order to gain expected improvements in revenue (improved vehicle attributes) and variable cost. Commonality would be lost in this case. The third option, New Intended Common development, entailed redesigning Intended Common components to meet the true needs of the truck and future SUV programs. The idea behind New Intended Common development was that the “correct” vehicle line (in terms of duty cycle and volume) was leading common part development. The SUV lines have strong incentives to utilize New Intended Common parts because of the significant economies of scale advantages gained by sharing parts with the truck program. In the case of New Intended Common parts, near-term commonality was lost between the current SUV and truck, with the intent of later regaining commonality in future SUV model years. Each New Intended Common part represents a potential opportunity for future commonality but implementation of all New Intended Common parts in future vehicle models is not guaranteed. The vehicle teams provided examples of New Intended Common parts that were implemented on follow-on SUV models, although a check could not be made of the actual percentage of New Intended Common parts that have been implemented in both product lines.

The Intended Common brakes are one specific example of the challenges the truck program faced in utilizing Intended Common parts. The brake example is presented here because it was widely cited by interviewees as indicative of the challenges associated with platform-based development. The Intended Common brakes were appropriately designed to meet the requirements of the heavier vehicle, the SUV. The full capability of the intended brakes was not required by the truck, meaning the truck design would carry additional variable cost and weight due to the increased, but unnecessary, braking capabilities. The truck team was pressed on both production cost and weight, meaning that a new brake design represented an opportunity for improvement.

Given that brakes were identified as an opportunity for improvement, the truck team identified and developed an alternative. The alternative to utilizing the Intended Common braking system was to make minimal modifications to the prior model year truck design in order to adapt the design to the new platform interfaces. Risk was similar between the two alternatives as both had previous production history. The modified prior model year truck design was better matched to the needs of the new truck, meaning that variable cost and weight would both be improved: production penalties would be reduced with almost no nonrecurring cost impact. In terms of the supply chain, the modified truck brakes would be produced by the same supplier that had supplied the prior model year brake components. The truck team most likely had strong negotiating power over this supplier as the supplier did not have the Intended Common brake production order for the SUV and would lose the truck business if the modified truck brake was not procured. While the truck team would lose the benefits of shared economies of scale, these benefits were believed to be minimal as previously described.

While the current production truck brakes provided the new truck team with a clear benefit in terms of variable cost and weigh, the benefits came at a loss to the SUV program. The truck team's decision to drop the Intended Common brake design meant that the Intended Common brake supplier would never reach the volumes that had been expected when the brake price was set for the SUV. Cancellation charges resulted and were absorbed by the SUV vehicle line. The vehicle team that had pursued commonality was now saddled with the financial cost of another program's decision to move away from commonality. This outcome highlights the interconnectedness of platform-based development decisions.

In the end, the truck program appears to have benefited significantly from common architecture, similar parts, and process carryover but has achieved limited direct carryover of Intended Common parts. Approximately 2% of the parts utilized in the truck are exactly common with the SUV parts. While similarity (a very difficult property to measure) across the vehicle lines would be expected to be much higher, the 2% commonality level demonstrates the difficulty of direct carryover of Intended Common parts in an environment with significant degrees of time separation between development programs. Ultimately, the penalties associated with maintaining commonality may have truly exceeded the potential benefits. The imbalance between benefits and penalties was likely exacerbated by the lack of truck program influence on the initial designs: the designs were not well-matched to the true needs of the truck program. Divergence resulted.

4.2.2. Observations

The vehicle platform program partially achieved its goals of creating shared parts, architectures, and processes across programs, while also beginning a cultural change at Company A. Some common parts have survived the large time offset in vehicle development efforts and where this has occurred, the truck team has reaped the benefits of reduced development time, testing, and a smoother production ramp. The number of Intended Common parts that have remained common (i.e., the same part number) is believed to be relatively low compared to initial plans, although a high degree of similar parts does exist and does provide partial benefits. In terms of the program's impact on Company A's culture, improvements have been made, although again, probably to a lesser degree than desired. While opinions about Program A were mixed, everyone interviewed was aware of the need to consider commonality. They understood the potential benefits (e.g., development cost savings, manufacturing cost reductions) and penalties (e.g., vehicle performance impact and potential revenue decrease) along with the challenges associated with implementation. The program has clearly started a cultural shift in the organization.

Specific observations:

1) **The program started with a well-developed plan for commonality that included identified opportunities for commonality; management processes for commonality; and the creation of a solid platform management team.**

2) **During the course of Program A, the emphasis shifted from developing common parts to sharing common architecture and similar manufacturing processes.** Commonality reduced with time as common parts were deemed infeasible, but similar designs remained and are believed to be beneficial in comparison to the alternative of independently developed parts. The similar designs enable some benefits such as mixed-model manufacturing at supplier sites and common or similar assembly processes. Partial benefits of commonality have been achieved and were only possible through a common starting point for the designs.

3) **The time offset (approx. 2 years) between development of the SUV and truck was too large, reducing the realized benefits of commonality within Program A.** This offset created several challenges. First, a decision making power imbalance existed across the two vehicles. This imbalance was created by the lack of resources placed on the follow-on variant (truck) during lead variant (SUV) development and resulted in uneven trade study discussions. The SUV team was well-into development and was able to produce detailed design analyses, while the truck team often had to rely on experience and judgment. The latter was not an effective negotiating tool against the detailed SUV trade studies. The result was a set of unacceptable design compromises made knowingly (truck study not properly weighted) and unknowingly (truck information unknown). Second, the large time offset increased the likelihood of a changing corporate environment and market conditions, both of which impacted the truck development decisions and negatively impacted commonality outcomes. An example of the changing corporate environment was an increased emphasis on cost reduction that was implemented after development of the SUV. This corporate initiative drove reevaluation of existing, Intended Common part designs.

When truck development ramped, the truck team had to pull back from common designs in order to meet vehicle attribute (e.g., performance) targets.

4) **Differences in the relative production volumes of the SUV and truck created asymmetric economies of scale benefits and therefore, different incentives to pursue and maintain commonality. Program A led with the lower volume product (the SUV), meaning the vehicle line with the lower recurring cost incentive to accept commonality (the truck) was left with the decisions of whether or not to reuse existing, Intended Common components.** Given the high volume manufacturing environment and relatively tight margins, shared economies of scale in manufacturing are a significant potential benefit of commonality. The fundamental driver for these benefits is the ability of a supplier to reduce its underlying costs through increased line utilization; implementation of lower cost processes that require higher minimum volumes; etc. Beyond passing along fundamental cost reductions, a supplier is often willing to manufacture higher unit quantities at reduced margins but higher net profits. These benefits diminish with increasing order volumes and may actually flatten out. For example, once the capacity of a production facility has been fully utilized, a supplier must procure additional production capacity, an outcome that requires an up-front investment and raises the fixed costs of production (e.g., overhead).

   The fact that the SUV production volumes were approximately one half that of the truck drove significant differences in the relative importance of shared economies of scale benefits. The SUV vehicle line stood to gain the most from the increased aggregate volumes, as volumes of common parts were tripled with respect to SUV unique parts. The SUV team had a high degree of price negotiation leverage, gained through incentives ("build many units a year") and penalties ("lose this business and you've lost several vehicle lines worth of production"). Suppliers were willing to give price discounts based on future expected order volumes associated with use of the common parts across both vehicle lines, a future outcome that was separated by two years. The SUV price benefits were estimated by the finance team to result in a 10% reduction in component price. In the case of the truck, common part volume was anticipated to increase by about 50%, with the cost savings being on the order of 1%. Clearly, the truck incremental economies of scale benefits were much lower than the incremental benefits to the SUV. (Figure 22 illustrates the concept of different economies of scale-based on production volume differences.) Given the limited economies of scale benefits, the increased costs of a more robust common part that has greater than needed capabilities from the standpoint of the high volume vehicle line cannot be offset in production. The incentives for commonality are reduced to nonrecurring benefits such as cost savings in development and test. General consensus from the interviews was that leading with the higher volume product (truck) would have been a more effective approach. The lower volume product had stronger economy of scale incentives to reuse truck development outputs than the truck had to reuse SUV outputs.

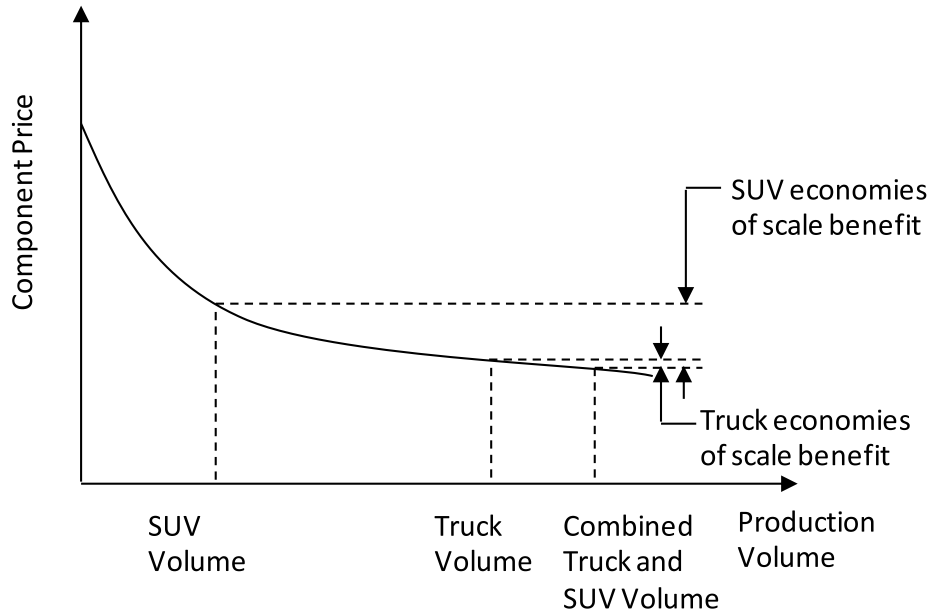

Figure 22: Economies of scale benefits due to part commonality provide greater benefits for the lower volume vehicle (the SUV) than for the higher volume vehicle (the truck). The reductions are a combination of amortization of fixed costs over an increasing number of units and of a supplier's willingness to operate at lower margins but higher net profits. (Chart is conceptual.)

5) **While the platform team's strong leadership was effective at driving commonality during SUV development, the team was dissolved too early. After the team disbanded, a "fox guarding the hen house" situation resulted as the common platform elements were handed over to the individual vehicle lines. Divergence occurred as a result and some of this divergence was likely non-beneficial.** Company A created a platform leadership team to manage commonality but did not maintain the team throughout the product family lifecycle. After completing the SUV development phase which included development of the Intended Common components, the platform leadership team was disbanded. The belief at the time was that the common parts were complete and would be automatically utilized by the truck team during its development cycle.

   While the vehicle teams supported commonality and clearly understood the benefits and penalties, each team was ultimately incentivized to make decisions that maximized its own profit. These decisions were not necessarily the best from the standpoint of Company A's overall profitability. The management of commonality was left to the functional engineering managers who were tasked with supporting the program managers and were subordinate to them in terms of decision making influence.

   Eliminating the platform leadership team before truck development avoided what would have been a source of conflict in the program: maintaining the platform leadership team through truck development would have ensured that tough discussions about commonality had occurred. As mentioned previously, initial "commonality" decisions were made with limited involvement from the truck team. During truck development, the team had a much better understanding of required vehicle attributes, which made justification of changes more robust. As with the initial platform and SUV development effort, truck era commonality decisions were mostly one-sided due to a lack of SUV engagement. (The platform team was gone and the SUV team was focused on "polishing" in preparation for production.) In both cases, engagement from the other program was necessarily limited due to resource availability and program focus.

6) **The combination of sequential development and platform development leadership team dissolution limited the effectiveness of "New Intended Common" part strategies during the early phases of the truck program.** "New Intended Common" parts that do not have a detailed implementation plan are unlikely to be implemented across products and effectively circumvent the challenges of common part development. After the case study interviews, the two vehicle programs were placed under a single program manager, a change that has significantly improved Company A's ability to leverage New Intended Common parts in future products.

7) **The follow-on variant (truck), never received a clear justification of the benefits of utilizing many of the Intended Common parts, yet faced very clear performance penalties that would have impacted revenues.** The truck team felt that it was being asked to compromise on revenue-impacting factors such as styling and performance without being given rationales for cost savings, reliability improvements, etc. The team could not make rational design decisions in support of commonality given the lack of demonstrated benefits; clear penalties; and the fact that commonality was only a mean to an end. Without clear demonstration of the benefits of commonality, unwind resulted.

8) **Pursuit of commonality has shifted from nearly blind executive support of commonality at all costs to applying commonality "where it makes sense."**

9) **In the case of the truck program, the number of exact part numbers carried over from the prior model year truck is significantly greater than the usage of part numbers that are common to the SUV.** Nine percent of the Program A truck components (exact part number matches) were carried over from prior truck generations while only two percent were shared with the Program A SUV. Development expense was likely much higher for the common components than for reuse of the prior model year truck components due to the added constraints associated with meeting multiple sets of requirements. The prior model year components were developed for that specific year vehicle and were also applicable to the future model year, although this applicability was not explicitly intended during the original development of these parts. The benefits of reuse from the prior model year were realized with little to no penalty. Benefits include minimal development time, reduced risk, and cumulative learning curve effects on price.

   It is important to realize that the carryover discussed above does not consider the benefits from component similarity, a design attribute that is extremely difficult to estimate. Similarity between the SUV and truck would be expected to be much higher than the level of commonality based on both interview comments and intuition. Likewise, similarity between the platform-based truck and prior model year truck would also be expected to be much higher.

10) **Program A was an attempt at convergence of two designs that had drifted apart from a common baseline.** This observation represents a repeated theme across platform-based development efforts. An initial platform vision pulls two or more products together based on the current understanding of market needs, newly developed technologies, and the underlying product designs. As development continues, the products pull apart due to reasons such as shifting market needs; shifting internal requirements; lack of coordination, and mismatches in program timing. Some of these changes are justified based on overall profitability increases, while others result in net profit reductions.

11) **A boundary exists between the platform team that "gets" commonality and is incentivized to act and the supporting functions (such as safety) that are trained to act upon independent programs.** Those outside the "commonality boundary" may contribute to divergence, or the reduction of commonality over time. Complex product development efforts, such as Program A, require input from the entire organization, supply chain, customers, etc. Many of these functional groups operate with a single product focus. As a result, these functional groups typically do not have the same understanding of the platform development effort as that of the core team. Crash test results are one such example: safety engineers will analyze crash test data and provide potential solution paths for issue resolution. These recommendations are made based on the specific vehicle and test, not the broader context of a vehicle family. Without proper interpretation from the core team, these recommendations can negatively impact commonality, and as a result, may have a negative impact on corporate profitability.

4.3. Case B: Military Aircraft, Lockheed Martin F-35 Joint Strike Fighter[21]

The F-35 is a supersonic, multi-role, 5th generation stealth fighter. Three F-35 variants have been derived from a common design. The variants use the same sustainment infrastructure worldwide and are initially planned to replace at least 13 types of aircraft for 11 nations. The goal is for the F-35 to be the most economical fighter program in history. The Lockheed Martin F-35 Joint Strike Fighter (JSF) case study examined the development history and current status of the three F-35 variants: Conventional Takeoff and Landing (“CTOL”, “A”); Short Take Off/Vertical Landing (“STOVL”, “B”); and Carrier Variant (“CV”, “C”). (See Figure 23.)

[21] The F-35 program would have been impossible to disguise. The Lockheed Martin team is gratefully acknowledged for allowing the results of this study to be made public and for allowing me to freely report my findings. While the Lockheed Martin team provided a factual review of this report, Lockheed Martin does not officially endorse the report’s contents: the opinions presented within this study are my own.

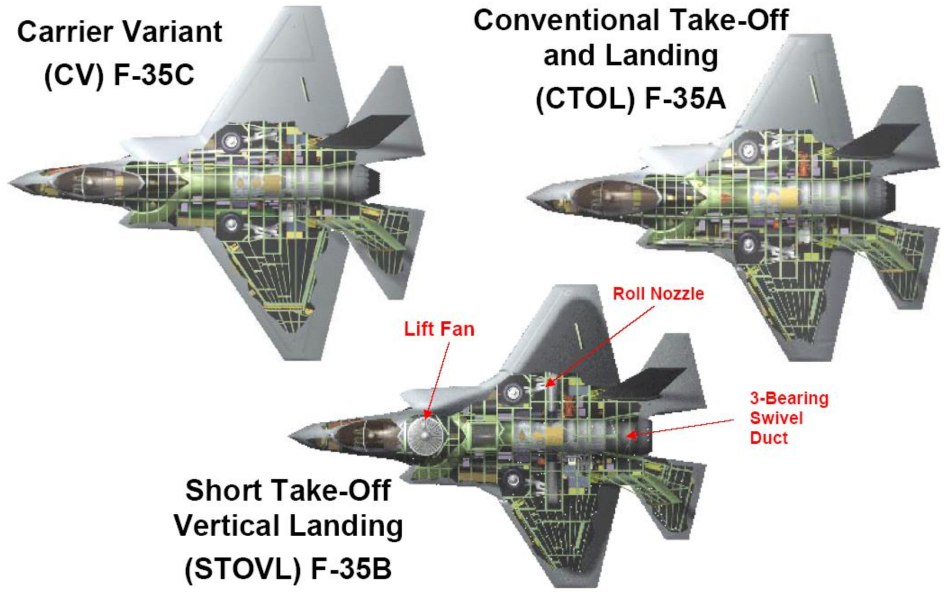

Figure 23: The three F-35 Joint Strike Fighter variants.

The field research portion of the case consisted of a one week site visit to Lockheed Martin's Fort Worth, Texas facility during the week of April 23, 2007. During this time, a total of 20 one-on-one interviews were conducted. Additionally, tours of the F-35 manufacturing line, development labs, and AA-1 aircraft (first production unit) provided context for discussions and case analysis. The publicly released F-35 literature was also reviewed.

4.3.1. Context

The majority of the United States' current fighter aircraft (e.g., F-16, F-18 A/B/C/D, A-10, AV8-B Harrier) were developed in the 1960's and 1970's; were manufactured in the 1970's, 1980's, and 1990's; and are approaching the ends of their useful service lives. The aircraft have already gone through multiple technology upgrades and service life extensions. Limitations such as age and a lack of stealth technology are strong incentives for replacement.

The F-35 Joint Strike Fighter is a critical element of the fighter fleet modernization effort. The program will address the needs of all the United States service branches and select international partners through the development of three highly common aircraft variants. The three F-35 variants will replace a broad array of aircraft, while complementing aircraft such as the F-22 and F/A-18 E/F which will have limited production quantities due to their high procurement costs. The F-35A (Conventional Take Off and Landing, CTOL) will replace the United States Air Force F-16 and A-10, and complement the F-22. The Marines will replace outdated F/A-18 and AV-8B aircraft with the F-35B (Short Take Off/Vertical Landing). The F-35C (Carrier Variant, CV) will replace the United States Navy's older F/A-18's while complementing its new F/A-18 E/F models. While production estimates are likely to change with time, the U.S. Government planned to purchase 2443 aircraft as of February 2007 and eight partner nations planned to purchase an additional 730 aircraft (JSF PSFD Memorandum of Understanding-Annex A, April 2007).

Given the scale and scope of the program, JSF represents the most expensive current defense procurement contract and the most expensive aircraft program in history. Current plans entail the development of the three variants at a cost of $44.5 billion; production of 2443 aircraft (U.S. Government only) and support equipment by 2027 at a total cost of $276 billion; and Operations and Support of these aircraft at an estimated cost of $347 billion (U.S. Government Accountability Office, March 2007). As is evident from these cost estimates, the development costs are dwarfed by production costs which are in turn greatly exceeded by operations costs. The program must carefully consider production and operations costs during the development phase: cutting corners in development could have dramatic lifecycle cost implications for the JSF program and for future defense spending.

Commonality represents a key program strategy for controlling development, production, and support costs. Three highly common aircraft variants are being developed to enable shared parts, processes, interfaces, and infrastructure. Lifecycle cost, lead time, and risk reductions are expected to result. Commonality is providing benefits in areas such as design reuse; mixed model manufacturing; shared economies of scale in manufacturing; common training; reduced logistics complexity; and improved maintenance. The program must constantly trade the potential benefits of commonality with penalties that may impact the team's ability to meet the unique needs of each service branch. The performance needs of the three variants are quite different, with the largest differences being driven by takeoff and landing requirements.

The approach of developing three highly common variants has taken fighter aircraft development complexity to a new level. The development of a single fighter aircraft is an extremely complex undertaking that involves thousands of people in a globally distributed supply chain. The JSF program is tasked with developing three highly common variants. Design problems are now constrained by the needs of three aircraft and a multitude of customers. Manufacturing and field operations must support not one, but three variants. The JSF approach is creating three aircraft with lower development cost, lead time, and risk in comparison to the alternative of three separate aircraft development programs, but increases these same factors with respect to any one of the individual program alternatives.

The JSF program is currently in its System Development and Demonstration (SDD) phase which is anticipated to last 12 years. The SDD phase of the program started in October, 2001 and is currently planned to run through 2013. The production phase will run through 2027 and Low Rate Initial Production (LRIP) has already begun.

4.3.2. F-35 Joint Strike Fighter Program History

For the purposes of this study, the F-35 history has been divided into the following sections: The JSF Program Roots; The Concept Demonstration Phase (CDP); System Development and Demonstration (SDD) Prior to STOVL Weight Issues; The STOVL Weight Attack Team (SWAT) Effort; The Revised Development Sequence and Continuation of AA-1; and Post-SWAT Development.

The JSF Program Roots: The Convergence of Needs, Prior Programs, and New Technologies

The roots of the JSF program represent a complex web of technology development, prior programs, and multiple sets of evolving needs, all of which were aimed at fighter fleet modernization. A simplified version of this history is illustrated in Figure 24 and discussed below. This section is based on public sources such as Kaminski (July 14, 1993), Sweetman (2004), Wolf (1998), and the F-35 (www.jsf.mil) and GlobalSecurity (www.globalsecurity.org/military/systems/aircraft/f-35.htm) websites.

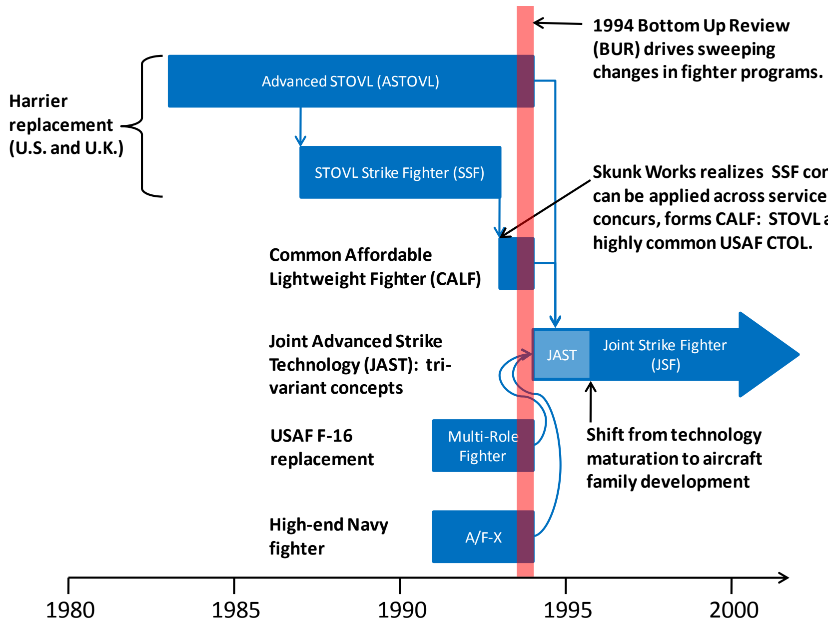

Figure 24: Simplified fighter program history as related to JSF. Commonality "root" is the STOVL Strike Fighter Program.

The 1980's highlighted the need for fleet modernization in all of the armed services, with the result being a series of programs (1980's and 1990's) aimed at producing a new generation of highly capable and more affordable fighters. The earliest program with strong links to the JSF program was the Advanced Short Take Off/Vertical Landing (ASTOVL) program conducted jointly between the United States and the United Kingdom with the intent being to identify a Harrier replacement. A black program, STOVL Strike Fighter (SSF), was started after partial completion of the ASTOVL program in order to investigate the potential for a supersonic stealth STOVL aircraft. The Lockheed Skunk Works executed this program from 1987 through about 1993. At that time, the Skunk Works realized that much of the SSF development was applicable to the needs of both the USAF and USN. Lockheed convinced the Department of Defense of the carryover potential and in 1994, the Common Affordable Lightweight Fighter (CALF) program was initiated with the intention of creating a STOVL and highly common USAF CTOL aircraft.

Two additional replacement programs were conducted between 1991 and 1993: the USAF Multi-Role Fighter (MRF) and the USN A/F-X. The former was an aircraft development program aimed at creating an affordable F-16 replacement, while the latter was intended to be a high-end replacement for multiple Navy aircraft and eventually USAF aircraft.

A sweeping defense review, the Bottom Up Review (BUR), occurred in 1993 (February through October) and had major implications for fighter development. The BUR assessed the need for five concurrent fighter programs: F-22, F/A-18 E/F, the A/F-X, ASTOVL, and the MRF. As a result, the USAF Multi-Role Fighter and USN A/F-X programs were cancelled; procurement rates were cut for the F-16 and F-18 C/D; and the F-22 and F-18 E/F programs were continued. Additionally, the BUR investigated the feasibility of a Joint Attack Fighter (JAF). The initial JAF vision appeared to be somewhat utopian: a single airframe would accommodate carrier and land operations; allow for supersonic flight; provide high and low end combat capabilities; and allow for a STOVL variant. Upon review of the concept, the Defense Science Board Task Force recommended a modified vision that would create two highly common variants to meet Air Force and Navy needs:

> "Broaden and refine the JAF approach to commonality to consider two different airframes, with a common engine (or engine core), common avionics architecture, common weapons, and a manufacturing process to facilitate efficient production of two different airframes and a high degree of cost commonality over the life cycle of the platforms. It will be necessary to undertake additional effort in concept development and demonstration, supported by an underlying technology program, before such a program can be developed. This approach is recommended for the long term needs associated with A/F-X and MRF." (Defense Science Board Task Force Report, July 14, 1993)

The Joint Advanced Strike Technology (JAST) program was created in January 1994 as a result of the JAF vision and Defense Review Board Task Force Recommendations. The initial purpose was to "mature technologies, develop requirements, and demonstrate concepts for affordable next-generation joint strike warfare" (www.jsf.mil), although the program quickly shifted from technology maturation to aircraft concept development through the absorption of the CALF/ASTOVL program in October of 1994. Incorporation of the CALF/ASTOVL program broadened the JAST vision from two variants to three and added an international partner: the United Kingdom had been a partner in the prior ASTOVL program.

A series of Concept Exploration studies funded as part of JAST produced results that strongly supported the tri-variant approach to meeting the needs of the multiple services. In particular, four of the studies were directly related to high level variant studies. Boeing, Lockheed, McDonnell Douglas, and Northrop Grumman were issued contracts titled "Tri-Service Weapon System Concept" or "Joint Weapon System Concept Definition and Design Research" with contract values ranging from $19.9M to $28.2M (1994). JAST became the Joint Strike Fighter program in August 1995 in order to reflect the shift in vision from technology maturation to aircraft development.

To summarize the pre-JSF history, the vision for the JSF program was formed over the course of approximately ten years rather than the outcome of a flash of inspiration. The services had aging fighter fleets and the need for modernization had spawned several development and technology maturation programs. One of these programs (CALF) had begun to explore potential overlap in needs at about the same time that the Bottom Up Review was exploring potential ways to do the same. As a result, JAST was created as a highly common two variant program but within a year had expanded to a tri-variant concept that would heavily leverage commonality to control costs. By the end of 1994, seven years prior to the start of the JSF System Development and Demonstration phase, the high level vision for commonality had been well-formulated as a result of the convergence of years of technology demonstration, cancelled prior programs, and a realization that the needs of the service branches were closer than previously believed.

The Concept Demonstration Phase (CDP)

The intent of the JSF Concept Demonstration Phase (CDP) was to demonstrate the feasibility of the tri-variant concept through actual flight demonstrations and to mature related technologies. Two companies, Lockheed Martin and Boeing, received contracts to design, produce, and test two demonstrator aircraft that would demonstrate three flight configurations: conventional, STOVL, and carrier. Per the JSF vision, the two aircraft were intended to be based on a highly common design. The Concept Demonstration Phase started on November 16, 1996 with two competing industrial teams led by Lockheed Martin and Boeing. The competition culminated with the selection of Lockheed Martin as the prime contractor for the JSF program in October 2001.

Both teams took different approaches in terms of their design concepts and flight demonstrators. Lockheed Martin's approach utilized the F-22 as a conceptual baseline along with a shaft-driven STOVL concept that had several years of prior development. Lockheed Martin built the CTOL variant (X-35A), demonstrated its performance, and then modified the exact same aircraft to demonstrate STOVL performance (X-35B). Carrier performance (X-35C) was demonstrated using the second aircraft. The ability to leverage the F-22 (including experience with the Pratt & Whitney F119 engine) presented a somewhat lower risk approach than that taken by Boeing. Boeing's concept relied more heavily on composite structures, more radical airframe shapes and a direct lift concept that proved to be a significant limitation. CTOL and carrier flight demonstration utilized the same aircraft, X-32A, with the second variant, X-32B, being utilized to demonstrate STOVL performance. (This paragraph is based on Sweetman, 2004. Refer to this reference for a more in-depth program history.)

At the beginning of CDP, both Lockheed Martin and Boeing were optimistic about maintaining high levels of commonality across the three variants. This optimism was in-line with the initial JSF vision. As an example of the high degree of commonality within the Lockheed Martin concept, the entire wing box and fuselage were common between the CTOL and STOVL configurations. Different leading edges, trailing edges, and tips were utilized to create all three wings. The Boeing concept utilized the exact same aircraft to demonstrate CTOL and CV capabilities.

As CDP moved forward, requirements were clarified, design knowledge increased, and the realistic commonality levels decreased within the Preferred Weapons System Concepts that were key final CDP deliverables. Boeing appears to have struggled the most with the requirements and design knowledge evolution and was heavily impacted by a 1998 Navy bring-back requirement (within JIRD 3), which drove its Preferred Weapons System Concept shift from a tailless delta wing configuration to a trapezoidal wing with stabilizers. The change occurred too late to be demonstrated by Boeing during CDP (Sweetman, 2004).

The resulting loss in commonality over time is visible in the commonality targets quoted by Boeing. In November 1996, Boeing JSF Program Manager M.O. "Mickey" Michellich was quoted as stating, "A fundamental benefit of our emphasis on innovation is the more than 90 percent commonality in parts and components among all three aircraft variants…A highly common airplane is the basis for affordability, not only in manufacturing and assembly but also into the operational life of the aircraft" (Boeing, 1996). By April 1998, Boeing had reduced its stated commonality target to 70% from 90%. At the same time, Lockheed Martin was aiming for 80% commonality (Wolf, 1998). The levels of commonality were dropping as both teams learned more about the needs of the individual services and the capabilities of their technologies and designs.

Manufacturing concepts were also investigated as part of the CDP effort and per the JSF vision of mixed model manufacturing. The three variants would be produced on the same line with highly common tooling. A high degree of part and manufacturing process overlap was planned as is illustrated in a Joint Program Office concept taken from a June, 2001 presentation (Figure 25).

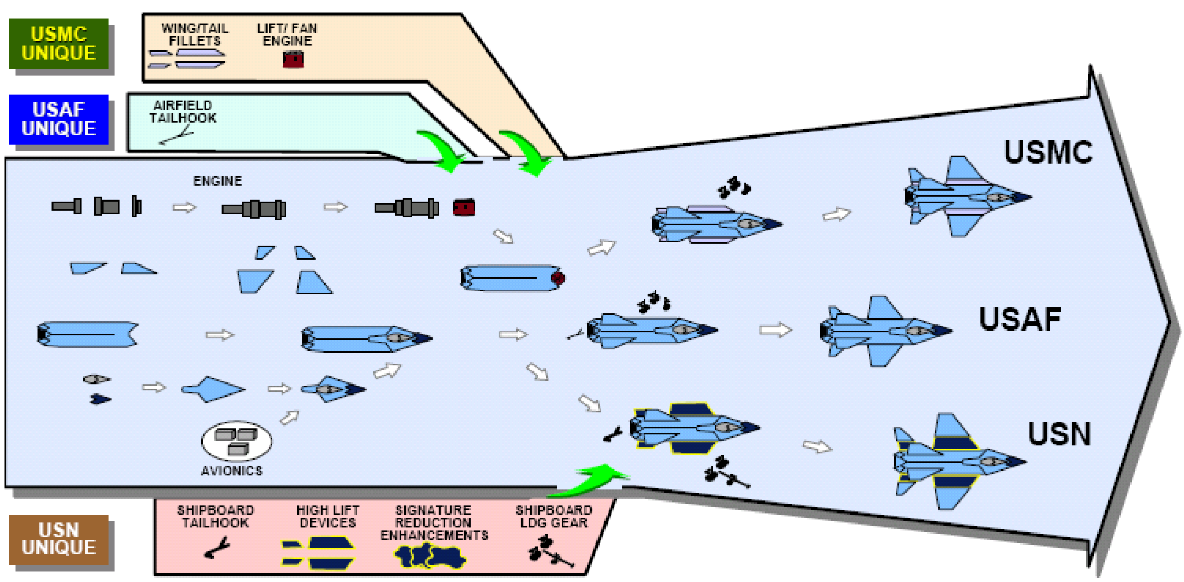

Figure 25: Simplified JSF air vehicle manufacturing concept. Source: Joint Program Office presentation (Lyons, Col. B., 2001).

CDP resulted in the successful demonstration of highly common aircraft meeting multiple sets of needs; maturation of associated technologies including manufacturing technologies; and initial investigation into production concepts. The CDP demonstrators had validated the ability of highly common aircraft to successfully meet multiple sets of "customer" requirements while still retaining a high degree of underlying commonality, the backbone of affordability. The technology and concept maturation originally called for by the Defense Acquisition Board Task

Force report on the JAF concept had been accomplished. The Joint Strike Fighter was now ready to move to the next phase of development. On October 26, 2001, the System Development and Demonstration contract was awarded to Lockheed Martin as the sole prime contractor for JSF.

System Development and Demonstration Prior to STOVL Weight Issues

System Development and Demonstration (SDD) started immediately upon the Lockheed Martin contract award in October of 2001 and, as the name suggests, was focused on development work that would enable a later production phase. SDD was expected to run through 2010 with a budget of $34.4 billion (U.S. Government Accountability Office, 2005). While Lockheed Martin was the prime contractor, the company had a large extended team that included BAE Systems and Northrop Grumman Corporation. In addition, the propulsion system contractor, Pratt & Whitney, was issued an SDD contract as the prime engine supplier with Rolls-Royce as the lift fan system provider. Development team participants also included the United Kingdom and other international partners, all of whom are anticipated to be future customers.

The goals of the SDD phase were very similar to the original JAST goals: create an affordable program through the development of a highly common tri-variant aircraft family and common manufacturing line. The expected benefits of commonality were a drastic reduction in development, manufacturing, and lifecycle operating costs. Based on the knowledge gained in CDP, the team realized that mission and vehicle systems would have the highest degree of commonality, while airframe commonality would be lower across the three variants due to the tight coupling between airframe designs and aircraft performance differentiation. Differences in the airframes would be required to enable STOVL capability (e.g., shaft-driven lift fan) and to meet the varying structural needs dictated by variations in operating conditions such as takeoff, landing, and flight load requirements. As an example, a carrier landing requires reduced approach speeds and imparts large vertical loads on the aircraft as it “drops” onto the aircraft carrier’s deck. The CDP single pilot, single engine configuration would be retained, as would the CDP demonstrators’ basic lines and external features. Mixed-model manufacturing would be utilized to leverage common tooling, training, and economies of scale.

Although the variants would be highly common, the message to each of the three services was that they would get their desired aircraft, regardless of the underlying platform. Maintaining commonality across the variants would provide the desired capabilities to each of the services at a much lower cost than could be expected through the execution of three independent fighter development programs. That said, meeting the requirements of the individual service branches was paramount to the JSF program’s success.

The purpose of the SDD contract was to move the JSF variant designs from a conceptual/ prototype phase into production-worthy and flight-proven aircraft. While the JSF concept had been demonstrated in CDP, the prove-out was mainly focused on demonstration of the ability to meet multiple sets of needs with a highly common aircraft, with the main CDP challenge being STOVL capability. The resource requirements associated with transitioning this work through the SDD phase were significantly higher than those required for the concept demonstration and proposal. As an example, the JSF proposal team consisted of between 100 and 200 people. The SDD team was over 4,000 strong within one year of the SDD contract start. The number of people involved in the program increased dramatically, as did expenses.

The initial SDD program strategy was to continue the parallel development of the three JSF variants and to culminate this effort in a tri-variant Preliminary Design Review (PDR). After the review, layout and detail design of each variant would start in a sequential manner, with one model being moved through a phase (e.g., Layout 1), followed by the next variant. While all three variants would be in development after the third variant was started, the variants would each be in a different phase of development. In this manner, the program would avoid staffing to fully support three variants in parallel and enable learning from one variant to be carried forward to the next. These staffing benefits applied to all aspects of the program including program management, engineering, manufacturing, and test.

The initial development order for the three variants was to be CTOL, followed by STOVL, and then CV; a decision driven mainly by the desire to reduce internal development risk. The CTOL variant was selected as the lead variant because it was "easy" to develop in relation to the more difficult STOVL version and because the CTOL variant had served as the baseline for all prior development effort: CTOL allowed STOVL lift fan complexity to be avoided for the first variant and was also the best understood of the three variants. The JSF team was preparing to embark on an extremely complex program and was about to do so with a newly formed team. The team would expand from a couple hundred at SDD start to over 4,000 in one year with a significant portion of the team makeup being new college graduates. In addition to the steep employee ramp, new development tools and processes were being rolled out with the JSF program, creating additional program risk and startup inertia. After development of the CTOL variant, STOVL would represent an incremental increase in complexity but would be addressed by a more experienced team, with well understood tools and processes. These benefits outweighed the fact that STOVL demand actually preceded demand for the CTOL aircraft. CV would follow CTOL and STOVL because demand for CV production aircraft was scheduled the farthest out.

The STOVL Weight Attack Team (SWAT) Effort

Per the program plan, the tri-variant Preliminary Design Review (PDR) was held in March 2003. At that time, the three variant designs were at varying levels of maturity. The CTOL variant was the furthest along due to the selection of the CTOL variant as the planned layout/detail development lead and the fact that it had historically been the baseline design that supported both STOVL and CV. STOVL was less defined, with CV being the least well defined at the time of the review.

CTOL layout started immediately after the March 2003 PDR and marked an important transition for the JSF program: the program had transitioned from the parallel development of the three variant concepts to sequential layout development, starting with the CTOL variant. While decisions would be made with consideration for all three variants, the majority of the focus was placed on developing the CTOL variant. STOVL capabilities (mainly the lift fan and ducts) would be added to the CTOL baseline to form the B variant, while the C variant would be formed by scaling certain aspects of the CTOL variant (Figure 26).

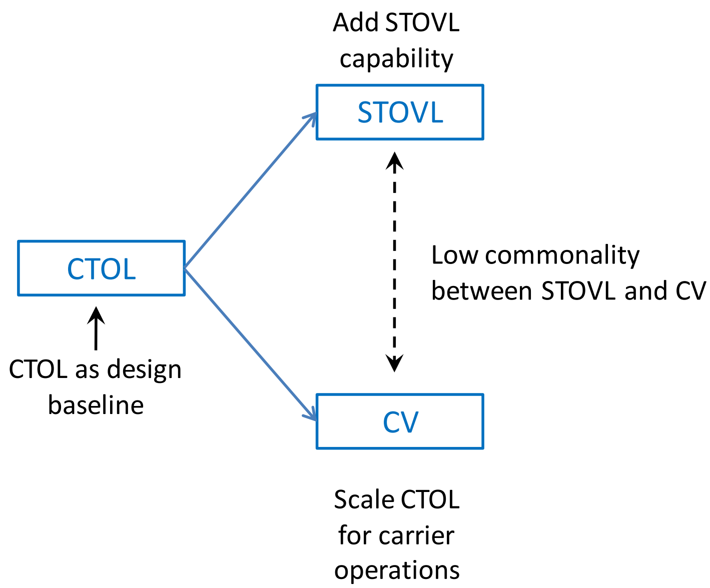

Figure 26: Design heritage in the early JSF history (prior to the STOVL Weight Attack Team effort).

Weight issues started to become evident during the summer of 2003, but the full extent of the problem took several months to fully quantify. Early in the development process, the team had to rely on parametric weight estimation techniques to produce "should weigh" estimates. These estimates were based on previous aircraft programs that were not platform-based. In addition to the normal degree of estimation error expected from a parametric model, error was further increased because the parametric models did not account for commonality-driven weight penalties. A bottom-up weight analysis (based on the actual aircraft variant designs) did not exist for any of the variants prior to the summer of 2003. As the CTOL design maturity increased during the summer of 2003, the team's ability to produce an accurate bottom-up CTOL weight estimate increased. Given the high similarity between the STOVL and CTOL variants, the STOVL weight estimate became much more accurate during the same period. The bottom-up weight estimation effort started during the summer of 2003 and by late 2003, the team knew that it had a major weight problem: the CTOL variant was deemed to be only marginally acceptable from a weight perspective and the STOVL variant was unacceptable given that it was approximately 3,000 pounds overweight. On April 7, 2004, the entire program came to a stop (Pappalardo, 2006).

The STOVL Weight Attack Team (SWAT) effort started on April 7, 2004 with a very clear goal: save the JSF program. A team of 550 people was dedicated to the SWAT effort, representing a significant departure from JSF's strong system team based approach that up until the point of SWAT had provided little organizational differentiation by variant type.

Given the urgency of the SWAT effort, the program team's philosophy shifted from common development to STOVL development. The impact of changes on other variants was always considered and in many cases, reported through processes such as completion of the 8-Square template. (The 8-Square template explicitly requires estimation of the lifecycle cost impacts of a change on the entire aircraft family. Cost impacts of a change are estimated for each of the three variants, *regardless of whether or not the change is being implemented on all three aircraft*. The template ensures a multi-product analysis of the impact of changes.) While impacts to commonality were considered, decision making was focused on STOVL weight reduction needs which were so severe that they left little room for commonality-driven compromise. All potential options were considered. Optimization of the airframe components for STOVL requirements became paramount to the program's success as these components represented a significant amount of weight; weight which is heavily influenced by variant-specific performance requirements. Penalties that had been introduced for the sake of commonality could no longer be accepted given the risk of program cancellation. Many small weight reductions were utilized to reduce the overall aircraft weight. Large gains in a few localized places simply weren't available given that aircraft, even common aircraft, are always designed with a strong sensitivity to weight in the first place. The resulting sweeping set of changes was referred to as "filing and grinding."

Several of the more significant weight reductions came from decisions to move away from architectural decisions that had been weighted too heavily toward manufacturability. For example, the original one-piece wing had carried a high degree of the aircraft loads in its skins, enabling a higher degree of commonality within the underlying wing structure. This design approach proved to be too costly in terms of weight and was undone during the SWAT program. Another manufacturability driven decision, the "snap together" fuselage module concept had been partially undone during prior design iterations and SWAT further reduced this approach. Through backing-off on the snap together concept, module interface weight was reduced at the expense of increased manufacturing assembly time and complexity.

SWAT also modified the common weapons bay requirement, a change that rippled across many components within the STOVL variant. Prior to SWAT, the internal weapons bays for all three aircraft were required to carry two 2,000 pound bombs and two missiles. As part of the SWAT effort, the STOVL requirement was changed to two 1,000 bombs and two missiles. The weapons bay doors were no longer common, given the smaller STOVL bay. The smaller STOVL doors in combination with the weight reduction imperative drove changes to the door actuator mechanisms, which no longer had to support the loads from the larger CTOL and CV doors. At an even further level of decomposition, the actuators themselves were optimized based on the anticipated loads at each particular location. The end result was a similar, rather than common, set of weapons bay doors and actuators. While some differences were anticipated initially, the full extent of the differences did not become apparent until detail design was nearly complete. Economies of scale had declined considerably from tri-variant, to single-variant, to within variant variation in some cases.

SWAT had a much lower impact on mission and vehicle systems due to their relative maturity at the start of SWAT and the clear cost to Lockheed Martin for any required changes. Due to the long lead times of many of the mission systems, their specifications had been set early in the SDD program, when understanding about the variant designs was limited and the team was relatively naive about airframe weight. By the time SWAT began, the systems were fairly mature and change proposals had high and very clear costs, given that Lockheed Martin would receive a bill for the changes that included supplier margins. (In other words, the expenses were probably higher and more tangible than the internal engineering investment in airframe redesign.)

The main sources of the STOVL weight issue appear to be attributable to four factors. First, the original aircraft design had been heavily focused on manufacturability, to the point that too much weight penalty had been accepted for the sake of manufacturing cost reduction. Second, the CTOL variant had been utilized as the STOVL (and CV) baseline and the high degree of carryover resulted in high weight penalties that were unneeded from the standpoint of STOVL performance. Initial optimism around commonality was too high and had to be undone by SWAT, in order to meet customer requirements. Third, the team was relatively new and the team's limited experience sometimes led to inefficient designs in terms of weight. The fourth factor was parametric weight estimation error, which had nothing to do with the actual aircraft weight, but rather with the team's ability to predict this weight. The parametric weight models have inaccuracies that were compounded by the novel, highly common tri-variant approach that was unrepresented in the past program data utilized to produce the parametric estimates. This last point is not highlighting a failure of the team as much as pointing to a reality of product development: initial estimates are based on limited information and have potentially large degrees of uncertainty.

SWAT closed the STOVL weight gap through three apparent change categories: STOVL specific optimization; improvements that were technically applicable to the CTOL and CV variants and were implemented; and improvements that were technically applicable but not implemented. The first class of change, design optimization was a significant strategy in weight reduction of the STOVL airframe. These changes by definition were unique to STOVL and clearly reduced commonality. A second class of change, those that were technically feasible and implemented on the CTOL and CV variants, maintained commonality in light of the STOVL requirements changes. Examples of these changes include systems improvements such as the cooling system architecture change. The third change category, technically feasible but unimplemented on other variants, represents lost technical opportunities for commonality.

Changes that fell into the last category were not necessarily "errors." Many opportunities for maintaining commonality with the revised STOVL designs were rejected by the team for affordability reasons: in these cases, commonality was possible from a technical standpoint, but not justified from an economic perspective. Commonality is a strategy rather than an end goal. The impact of each change had to be examined, and was examined, from the perspective of the overall family and the individual variants. Changes that were justified for STOVL did not always make sense for the other variants due to differences in the relative priorities placed on weight reduction and cost. A change that was justified based on the relatively high STOVL weight reduction thresholds[22] (either required development investment per pound of weight reduction or recurring cost incurred per pound of weight reduction) was not necessarily

[22] "Weight reduction thresholds" are the limits established by the program to determine whether or not a given weight reduction opportunity is worth pursuing. A development (Non-Recurring Engineering) threshold indicates the maximum amount of money the program is willing to spend (cost/pound) to remove weight from the design of one or more variants. A similar threshold exists for weight savings that require increased recurring costs. Various types of weight reduction thresholds were observed in all three of the aircraft cases associated with this research.

justified for the CTOL or CV variants. While still important, weight was less important in the case of CTOL and CV relative to STOVL. Additionally, there were likely some, possibly many, changes that were applicable to the other variants and not implemented due to coordination challenges in such a complex program. The relative proportions of the change categories, proper versus improper decision making, etc., are impossible to determine.

The SWAT effort was a tremendous success in terms of saving the JSF program, although the effort did contribute to cost and schedule overruns that were addressed by the SWAT-era re-plan. The re-plan included an SDD cost increase of $5 billion; an 18 month SDD schedule extension; and the delay of the first CTOL flight by one year. While the re-plan was triggered by SWAT, SWAT was only one contributing factor in the cost and schedule delays.

The Revised Development Sequence and Continuation of AA-1

As a result of SWAT and the program re-plan, a decision was made to follow STOVL development with a second "optimized" CTOL design that would leverage the detailed STOVL design and prior CTOL development. The program re-plan had effectively changed the order of the three variants: STOVL became the new lead variant, to be followed by CTOL (optimized), and then CV. The "difficult" aircraft was now the lead variant, with STOVL designs being potentially carried forward to CTOL and CV development work. The STOVL, CTOL, and CV layouts each took about one year and were started about 6 months behind one another.

As part of the re-plan, the team was faced with the question of what do with the original CTOL design, the first of which was nearly ready to be manufactured. The team had two options: either complete the first CTOL design (AA-1) and follow through on its manufacture or cancel this development and manufacturing effort. The AA-1 design was nearly 70% complete at the time of SWAT initiation, meaning much of the development investment had already been sunk. Cancelling AA-1 would have enabled the organization to focus its full resources on SWAT and the follow-on CTOL and CV variants, while avoiding the initial AA-1 manufacturing build. Cancellation would also have limited the value of the initial CTOL development effort to a design exercise. The team chose to continue with AA-1 development and production in parallel with the STOVL variant. While this approach resulted in stretched design resources due to the parallel development of AA-1 and STOVL, carrying on with AA-1 enabled manufacturing to start to build its processes and tooling; the supply chain to ramp up; and testing to begin. To summarize, AA-1 has enabled significant learning and risk reduction through development, production, and flight testing that would have otherwise been delayed. To quote one of the JSF team's terms, AA-1 was a "pipe cleaner."

Post-SWAT Development

While the post-SWAT development phase has entailed tremendous amounts of effort, at a high level, development appears to have proceeded to plan, in terms of development sequence and vision implementation. The 2004 program re-plan associated with SWAT created a combined and delayed CTOL/STOVL CDR for the first quarter of 2006 and scheduled the CV CDR for about one year later. The combined CTOL and STOVL reviews were completed on February 17, 2006 and by June 2007, the CV CDR had been completed. AA-1, the early CTOL variant, made its first flight on December 15, 2006, and the first STOVL aircraft, BF-1, is readying for a test flight in spring 2008. Production of the first CV commenced at BAE Systems in October 2007. System Development and Demonstration is expected to be completed in 2013 at which point fully operational aircraft models will have been tested and demonstrated.

4.3.3. Commonality Data Analysis

Access was granted to the Affordability Team's historical commonality metrics[23] which provided an excellent opportunity to perform a quantitative check of the interview results. The metrics are based on part/subsystem weight due to the lack of early design definition inherent in any development program. As was mentioned previously, the earliest weight estimates were based on parametric equations and then transitioned to part weight estimates as detail increased. The available data is divided into categories for the entire air vehicle with propulsion; the entire air vehicle without propulsion; mission systems; vehicle systems; and the airframe. Each part/subsystem is classified as being either common, cousin (80% of the benefits of a common part), or unique as defined by the U.S. Government. The weight-based commonality metrics were organized and plotted for each aircraft variant and category. All data is included in Figure 29 through Figure 32 with the exception being the data for the air vehicle without propulsion.

The metrics histories have several limitations that influence the degree to which they accurately represent the JSF variants' commonality history. That said, the metrics still provide valuable information regarding the overall trends associated with commonality. The metrics also represent the program's attempt to use the best available information to better understand commonality and its evolution. The data provided by the program represents the best identified tracking of commonality within the seven case studies. Several limitations are listed below:

- The metrics consider parts only, meaning that that they only partially describe the commonality "picture." These metrics provide no information about process commonality in areas such as manufacturing, logistics, and operations, all of which represent significant areas of potential cost savings.
- The metrics are weight-based and are not directly related to cost. A high cost common part may have a low weight with the result being a low impact on the commonality metrics presented here, yet very important cost implications.[24]
- When examining the following data analysis, it is important to keep in mind the relative cost differences between the different categories. The airframe (and program management) costs account for approximately 45% to 60% of Unit Recurring Flyaway costs; systems (mission and vehicle) cost approximately 30% to 35%; and propulsion accounts for 10% to 20% (Figure 27). Airframe components are less likely to be replaced

[23] Commonality metrics (percentages based on weight) were provided for multiple time periods. Raw data, such as individual part identifiers and their associated weights, were not provided.

[24] The reader is reminded that cost information did not exist during the early phases of SDD. Weight was the best available metric for tracking commonality. The team is starting to track cost-based metrics, along with the weight-based metrics, as better design information becomes available.

throughout an aircraft's operational lifetime, deemphasizing their importance in relation to the lifecycle costs of mission systems, vehicle systems, and propulsion.

- The three variant designs were at varying states of design maturity throughout the early years of the JSF SDD program. This fact makes the estimates for the STOVL and CV variants less certain than the CTOL estimates, especially in the earlier years of SDD.
- The data spans the SDD period of development, starting with November 2001 and continuing to October 2007. The early vision (pre-SDD) and design evolution are excluded.
- For the purposes of this data set, a common part is defined as being common between two or three variants. While there are differences between the two classes of commonality, the historical metrics claim the same benefit regardless. Two-variant commonality is evident in Figure 28. For example, the CTOL and STOVL vertical stabilizers are shown as common parts in this figure.
- The metrics represent percentages of total weight, a parameter that varies across the three aircraft and also through time within a given aircraft model. A common component impacts each variant's commonality metric differently due to differences in the total weight of each aircraft.
- Definitions of cousin parts have changed over time, resulting in some degree of change induced solely by changes in definition.

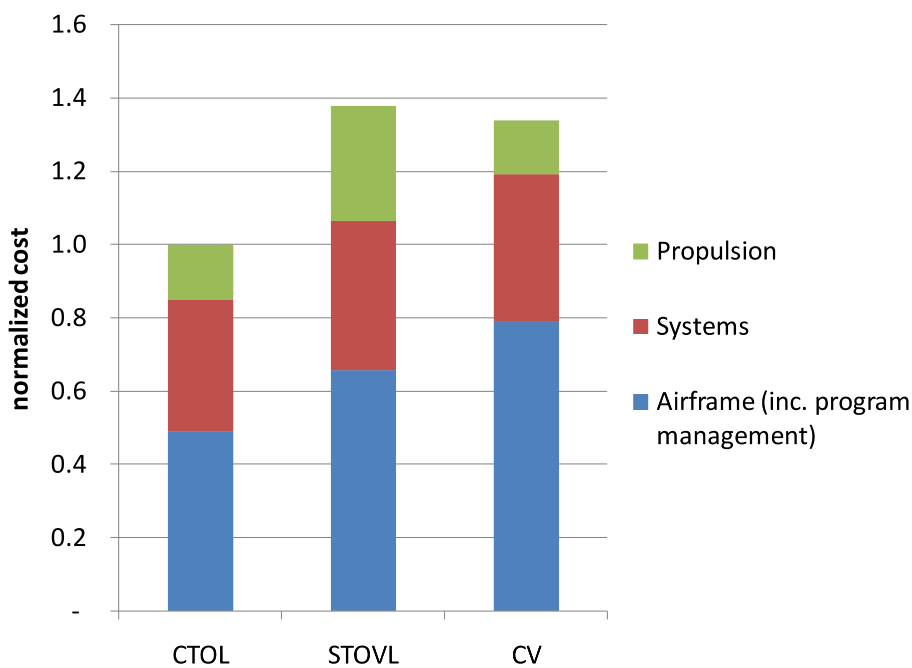

Figure 27: Rough cost breakdown by major category and variant.

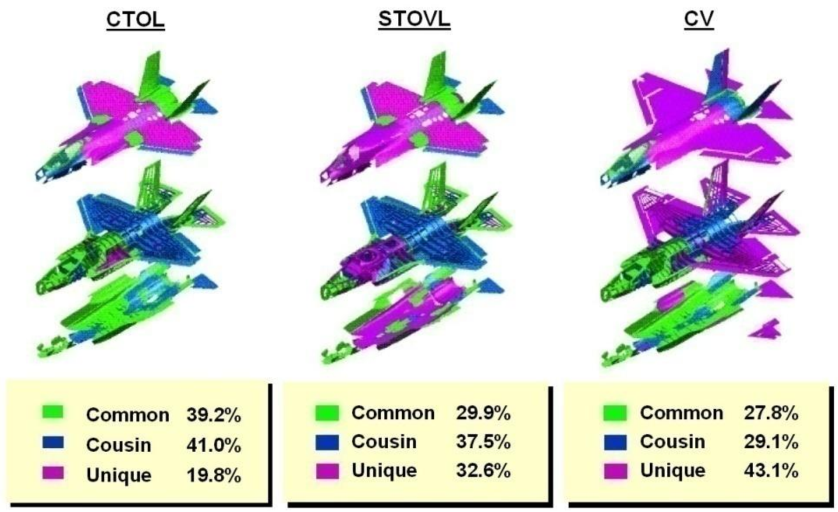

Figure 28: Graphical view of JSF airframe commonality based on February 2004 data. The color coding illustrates the definition of "common" as being common to any two or more variants, rather than common to all three. (Illustration source: www.jsf.mil. Accessed July 6, 2006. Matches February 2004 Lockheed Martin data.)

In terms of the overall air vehicle with propulsion (Figure 29), part commonality has generally decreased between the start of SDD (November 2001 data) and December 2006 for all three variants, while there has been a noticeable increase in reported commonality for the latest data points (October 2007). The largest decrease has occurred within the CTOL design which started at 74% commonality and reached a low of 54% in October 2005, a period that should have captured the majority of the SWAT-induced changes. During this period, both the STOVL and CV variants lost approximately 11% of their commonality with the other variants (51% to 40% and 55% to 44%, respectively). During the same period, unique parts increased from 5% to 17% for the CTOL variant; from 29% to 37% for the STOVL variant; and from 31% to 39% for the CV. The reader is reminded that the CV variant was the most unique to begin with and also the least mature at the time of SWAT.

Also visible in Figure 29 is the fact that the CTOL variant has always had the highest degree of commonality by between 9% and 23%. This observation points to the fact that the CTOL variant had served as the baseline for STOVL and CV concept development until the time of SWAT. (Refer to Figure 26.) The metrics point to both the CTOL baseline and the accounting decision that labels any part that is common to two or more variants as "common." Commonality between the STOVL and CV variants was reported to be limited during the interviews and this comment is partially supported by the data.

It is important to note the increase in air vehicle commonality that has resulted between October 2005 and October 2007. CTOL has increased from 54% to 58%; STOVL has increased from 40% to 45%; and CV has increased from 44% to 49%. The JSF team explained these increases to be a combination of changes in commonality accounting and design maturation (especially CV) that has resulted in increased commonality.

Figure 30 illustrates a consistent theme expressed throughout the JSF program vision, history, interviews, and data: the mission systems are almost 100% common. The 90% commonality associated with the CTOL variant reflects the fact that the CTOL variant is the only variant that has a gun and the gun is heavy. Since commonality is normalized to each aircraft's weight, the COTL variant has a higher relative unique weight and lower common weight percentage. The mission systems trends are consistent through time.

The evolution of vehicle systems commonality is illustrated in Figure 31 and shows several significant changes. CTOL vehicles systems commonality reduced by 18% between September 2003 and December 2004. The bulk of this loss of commonality (13% of total systems weight) resulted in an increase in unique parts. STOVL vehicle systems commonality reduced by the same amount between February 2004 and October 2005. In the case of the STOVL variant, the bulk of the change (17% of the 18%) was from common to cousin parts. STOVL vehicle system commonality has actually increased by 6% between December 2006 and October 2007. Also noteworthy is the relatively high percentage of CV unique vehicle systems ranging between 46% and 61% unique throughout the SDD history. The high level of unique vehicle systems has been driven by the larger size of the aircraft. As an example, the Electrohydrostatic Actuation System (EHAS) has been upsized to supply the larger required actuation forces of the CV. While an initial strategy of using higher capability actuators from the CTOL and STOVL variants in lower capability areas of the CV version has not completely materialized, there is still a reasonable amount of similarity across the electrohydrostatic actuators and electronic units (power and controls).

Figure 32 demonstrates the relatively low levels of commonality achieved in all three airframes in comparison to the mission and vehicle systems: at the lowest point (October 2005), the CTOL, STOVL, and CV were 26%, 18%, and 19% common, respectively. These numbers have since rebounded due to a combination of accounting changes and improvements in commonality with design maturation. The largest improvements were in STOVL airframe commonality (from 18% to 29%) and CV airframe commonality (from 19% to 30%) between December 2006 and October 2007. During the same period, CTOL commonality increased from 26% to 34%. It is important to note that the airframe commonality levels started lower than the other systems, with the highest starting point being the CTOL variant at 53% in November 2001. This lower commonality is attributed to the need to optimize airframe weight and the fact that the need to optimize was well understood early in the JSF program (CDP). Give the lower starting points for commonality, the relative changes in airframe commonality levels are more significant than in the mission and vehicle systems. For example, between September 2003 and December 2004, the STOVL variant lost 50% of its initial airframe commonality.

Cousin and unique part levels are relatively high in the airframe compared to other subsystems, with the exception being the high uniqueness of CV vehicle systems. The CTOL airframe has the highest cousin part percentages which have typically been over 40%. The STOVL airframe is second, followed by the CV airframe which has fluctuated around 30% cousin. To the extent that optimization was achieved through changes such as metal gauge thickness, a part was able to maintain a "cousin" designation. Maintaining "cousinality" between airframe components appears to be easier than maintaining cousinality between vehicle systems, CV vehicle systems excepted. Also, as with CV vehicle systems, the CV airframe exhibits the highest degree of uniqueness due to its size and carrier operations requirements.

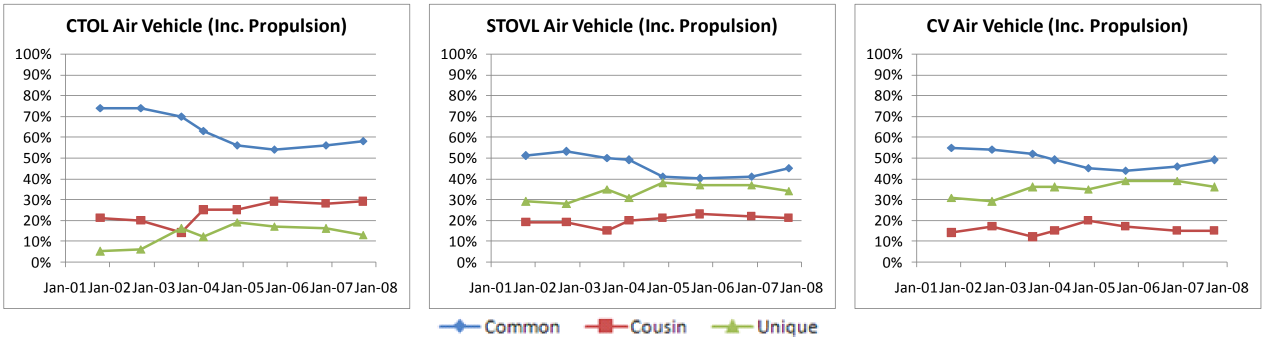

Figure 29: Air vehicle level commonality (propulsion system included).

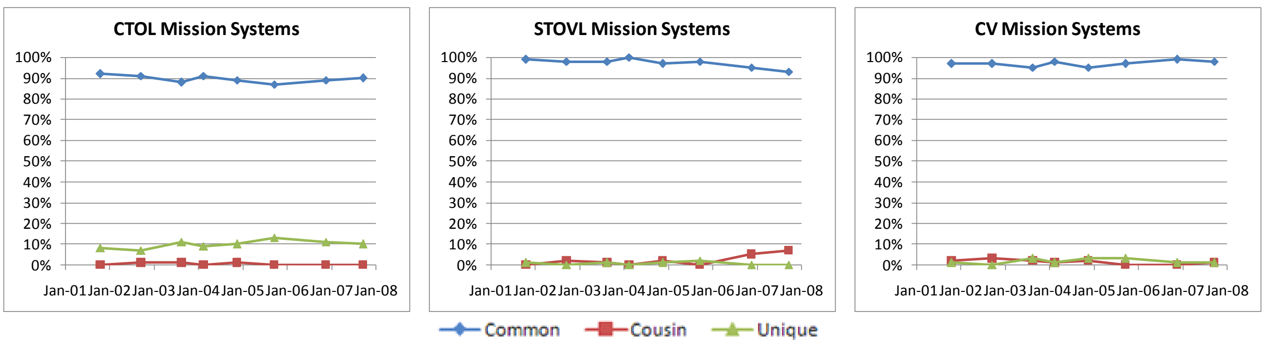

Figure 30: Mission systems exhibit very high levels of commonality and stability over time. The only significant difference across the variants is the CTOL gun which drives commonality down and increases uniqueness.

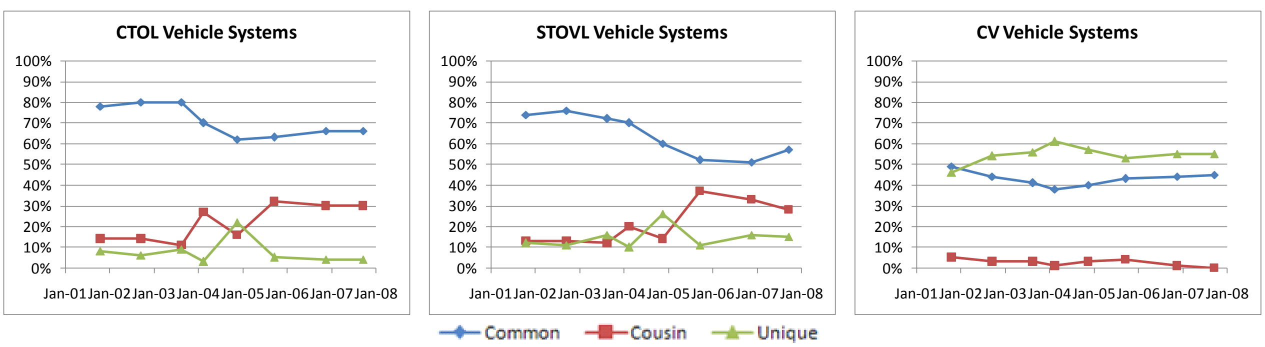

Figure 31: Vehicle systems commonality is considerably lower than mission systems. (The December 2004 anomaly is attributed to a definition change for the landing gear).

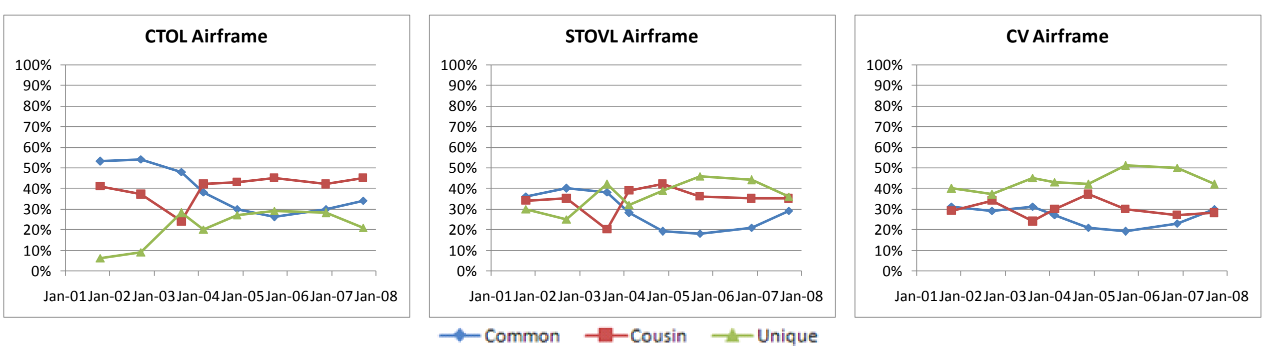

Figure 32: Airframe commonality levels are by far the lowest. Common parts have, for the most part, decreased with time while unique part levels have risen. This trend is reversed for the final data points and in some cases, for the last two data points.

4.3.4. Additional Discussion of Commonality

At a high level, the JSF team has achieved strong success with respect to commonality-driven affordability: development of the three variants is expected to cost less than the independent development of two aircraft; the aircraft are produced on the same manufacturing line; and significant lifecycle cost benefits are expected in areas such as global logistics, operations, and training. At this time, the degree to which manufacturing and lifecycle cost benefits will be realized is difficult to accurately predict, given the lack of production and operations history. As aircraft are produced and operated, the significance of the savings associated with the tri-variant approach will become more clear.

While clearly successful over the alternative of independent development, the extent to which part and module level commonality has been achieved appears to be lower than initial expectations. The reduction in commonality in comparison to initial expectations is evidenced by a comparison between the early 80% commonality target (Wolf, 1998) and the data analysis in the previous section. Air Vehicle commonality levels of 80% are only achieved through the addition of common and cousin parts.[25] As an additional high level example, the highly successful engine development program (Figure 33) has not achieved the initial vision of complete interchangeability of engine cores across the variants. While the Pratt & Whitney F135 and GE F136 engines are stated to be interchangeable for one another, different engine variants are required for each of the three aircraft variants. The engine must support a shaft-driven lift fan in the case of STOVL operation, requiring a weight penalty of approximately 100 pounds. This penalty has not been accepted in the CTOL and CV versions. While highly common, the engines are partially different from the perspectives of parts, manufacturing assembly, global logistics, and maintenance.

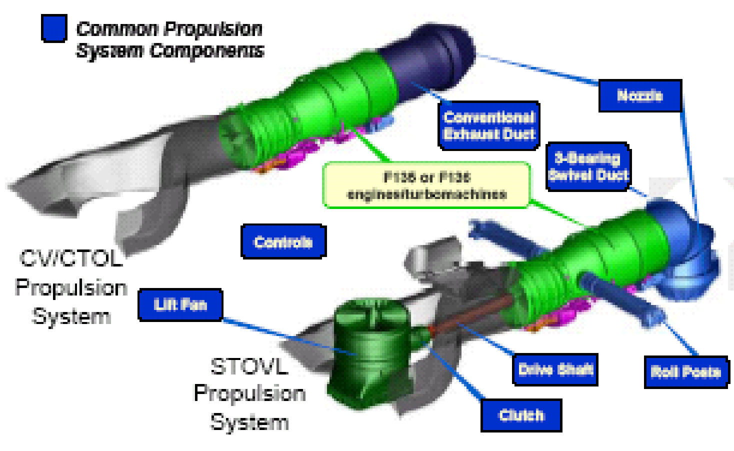

Figure 33: JSF engine commonality has been highly successful, although the full vision of swappable engine cores has not been realized. The penalties for a common core were not justified from performance and affordability perspectives. Graphic source: International Participation Study (June 2003); use of Lockheed Martin data.

[25] The reader is reminded that the commonality metrics presented in this report are weight-based. A cost-based estimate may provide higher levels of cost commonality, although this information was not available for the study.

As learning has occurred and requirements have changed, the team has had to shift from a strategy of common parts and assembly processes to a strategy of cousin parts and common processes. The result has been a decline in commonality within many areas of the aircraft. This strategy has allowed the JSF team to realize many of the benefits of commonality while avoiding the performance penalties associated with excess weight, particularly in the case of the STOVL variant.

4.3.5. Observations

1) **The U.S. Government's decision to structure the JSF program as a family of three related aircraft variants represents the most important commonality decision on the JSF program. This high level decision has created a program that is on track to develop 3 fighter aircraft variants for the cost of 1.8.** Through consolidation or cancellation of existing programs and the creation of the tri-variant JSF program, the U.S. Government drove significant savings relative to the alternative of three independent development programs. The high level vision of a common air vehicle, a common engine, and a common manufacturing line created the proper starting point. Without the structure created by the government, Lockheed Martin and the extended JSF team could not have pursued this approach.

2) **The vision for commonality represents the result of a long history of interconnected ideas.** The Lockheed Skunk Works proposal for the Common Affordable Lightweight Fighter program (1993), followed by the Bottom Up Review (1994) were the most obvious contributors to the JSF vision. In addition, programs such as the STOVL investigations in the 1980's laid the technology foundations for the JSF program.

3) **While lifecycle commonality benefits exist, the immediate development (nonrecurring) cost benefits of a tri-variant program were substantial enough to justify pursuing commonality.** The "3 for 2" cost mentioned above represents a compelling development savings that justifies pursuit of commonality as long as the lifecycle benefits are either neutral or positive with respect to three independently developed aircraft. Production, operations, and support cost benefits are also expected, further solidifying the case for commonality.

4) **Throughout the program history, the emphasis on commonality has shifted from the pursuit of common parts and processes to the pursuit of cousin (similar) parts and common processes. The primary driver for this shift was increasing knowledge about the true design differences between variants.** The initial vision was focused on high commonality across the entire aircraft with Lockheed Martin quoting an 80% commonality target in 1998 (Wolf, 1998), prior to SDD start. The vision consisted of a highly common air vehicle (which decomposes into the airframe, mission systems, and vehicle systems), a common engine, and a common manufacturing line. The common manufacturing line implies high degrees of manufacturing process and tooling commonality.

   Part commonality has been achieved in varying degrees on the JSF program. Mission systems have achieved a very high degree of commonality as is visible in Figure 30. Vehicle systems have achieved commonality to a lesser extent (Figure 31) and have experienced a reduction over time. Airframe commonality has experienced a similar reduction but started at a lower initial level (Figure 32). Reduced airframe commonality came as no surprise to the JSF team, given the widely varying service requirements and high weight of the airframe. Airframe components are less likely to be spared and replaced during the system lifecycle, reducing the potential lifecycle cost benefits of airframe commonality in relation to mission systems, vehicle systems, and propulsion systems which tend to be serviced and replaced throughout the lifecycle of a given aircraft.

In many cases, similar (cousin) parts have taken the place of previously common parts. These parts retain some of the benefits of commonality such as similar design baselines; similar part manufacturing processes; and similar or identical assembly processes. Performance penalties, such as weight, are reduced. The airframe utilizes the largest number of cousin parts, due to the use of similar geometries that have been scaled in some manner to support differing dimensions or loads.

The general reductions in part commonality have been caused primarily by the increasing design maturity with time, a fundamental aspect of any product development effort. Early in the SDD phase, the designs were not well understood and could not be well understood given the limited resources assigned to proposal creation. At a high level, the designs appeared to be common. The degree to which specialization was required became increasingly apparent as each variant was developed. Divergence resulted.

While part commonality may be lower than initially intended, manufacturing commonality (including processes and tooling) has been very successful. First and foremost, all three variants are produced on the same manufacturing line with highly common tooling. Especially important is the commonality in expensive tooling such as the automated joining tools and moving assembly platforms.

5) **The U.S. Government definition of a cousin (similar) part is more limited than Lockheed Martin's definition, limiting Lockheed Martin's ability to "take credit" for the full benefits of commonality. Unit Recurring Flyaway (URF) and lifecycle cost estimates may be overinflated as a result.** Both Lockheed Martin and the U.S. Government define a common part as being physically interchangeable (i.e., having the same part number) but the two differ in the definition of a cousin part and the associated benefits. The U.S. Government defines a cousin part as having the same material, function, and interfaces, along with similar geometry. In terms of manufacturing, a cousin part must be produced with a common fabrication method or assembly tooling although modifications may be made to machining paths or tooling templates. In terms of benefits, the team may take credit for cousin parts at 80% of the production benefit of a common part.

Lockheed Martin contends that the government definition is too narrow in several regards. First, the process benefits of a cousin part are a mirror image of the procurement benefits, even though assembly processes and tooling can accept much higher levels of variation, if the part and process have been properly designed. For instance, if an assembly is determined to have 30% common parts, 20% cousin parts, and 50% unique parts, the manufacturing benefits will be calculated on the same percentage basis. The result might produce an underestimation of the "cousinality" assembly cost benefits, and therefore, an overestimation of the Unit Recurring Flyaway (URF) costs. Second, a material change immediately drives a unique part classification, again avoiding any potential benefit realization from a high degree of similarity. Third, the definition of a cousin part is rigidly defined as providing 80% of the benefit that would have been realized had a common part been utilized. While this rigid definition is probably required to simplify the design auditing process, the reality is that actual benefits may be either higher or lower than the 80% level.

6) **Although commonality has been an important element of the JSF program, "Commonality has never been an objective of the program. It is a strategy."** Both Lockheed Martin and its customers have appropriately viewed commonality as a potential tool for achieving improved development and lifecycle affordability. The customer desires an affordable aircraft that performs to requirements. Many commonality opportunities have been appropriately rejected by the JSF team due to affordability reasons.

7) **Differences in the relative production volumes of the three JSF variants have created differences in the recurring cost benefits of commonality from the perspective of each variant. The variant production numbers impact learning curve traversal rates and economies of scale.** The recurring cost benefits of commonality are primarily driven by learning curve traversal and economies of scale which depend on the total production volume and rate of a given part. Based on the JSF latest available production estimate of 3173 aircraft (JSF PSFD Memorandum of Understanding- Annex A, April 2007), the CTOL variant has much higher expected production volumes (2298 units) in comparison to the STOVL variant (535 units) and the CV variant (340 units). The CTOL variant has less incentive to accept compromises for the sake of recurring cost reduction in comparison to the CV: the CTOL volume on a CTOL/CV common part would be 2638 units rather than 2298 units for a CTOL unique part, an increase of 15%, while the CV volume for a combined part would also be 2638 units rather than the 340 units for a CV unique part, an increase of 675%. The high volume part descends the learning curve at a faster rate than the low volume part. Likewise, the mixed model part is consumed at aggregate production rates, creating an economy of scale benefit.

   The C variant has the lowest expected production numbers; in many cases, requires the highest capability; and also has the lowest commonality levels between it and the other two models. The result of low volume, high required capability, and uniqueness can be expected to drive significant lifecycle cost increases for this model. Example: CV Electrohydrostatic Actuation System (EHAS) costs are twice that of the CTOL and STOVL variants due to increased capability and lower production quantity for the CV aircraft.

8) **While the initial concepts for the three JSF variants were created in parallel, layout of each variant (post-PDR) started sequentially. Sequential development likely contributed to the extent of the STOVL weight problem and to reductions in commonality. Resource limitations were the primary drivers for sequential development.** A strong vision for commonality was developed through extensive studies and test, both within and prior to the JSF program. During the initial phases of SDD, the STOVL and CV concepts typically leveraged the CTOL variant as the design baseline, although all three variants were actively considered during conceptual work. Parallel development ended with the Preliminary Design Review.

The layout and detail design phases for the CTOL, STOVL, and CV variants were started in series due to resource limitations. Resource requirements increase significantly with shifts from conceptual design into layout and then again into detail design. Staffing (and training) a team large enough to support all three variants at once made no sense. The CTOL (optimized) and CV variants were ramped as resource requirements decreased for the prior variant. CDR's were separated by about 6 months with the development cycle being approximately 18-24 months long for each variant.

Sequential development and the heavy reliance on the CTOL variant as a baseline likely contributed to STOVL weight issues and the resulting program re-plan. Additional depth around the STOVL (and preferably, CV) concept would have improved visibility into each variant during the early stages of the program. The previously mentioned STOVL weight reductions that were not carried over to the other two variants for economic reasons, may have returned an economic benefit, had they been discovered earlier. Resource limitations precluded a parallel approach.

9) **The JSF program's approach to commonality has been to start with a previous variant as a baseline and then to modify this baseline as required and justified by analysis. Starting from a common baseline and backing off has produced a design with much higher levels of commonality and similarity than would have been achieved through independent development efforts.** The conceptual work associated with CDP and the work prior to SDD PDR, while conducted in parallel, heavily relied on the CTOL design definition and deviations from this definition. When the team shifted to detail development and a mostly sequential approach, CTOL was maintained as the initial baseline for the STOVL aircraft. The development order was AA-1 (first CTOL), STOVL, CTOL (optimized), and then CV. Subsequent variants leveraged prior development but were not strictly held to the prior model decisions and constraints. According to Terry Harrell, Director of Air Vehicle Development, "We rarely tried to enforce commonality that didn't work out naturally in the evolution of the design over time." Divergence in the design was required in order to produce variants with acceptable performance. The alternative to starting from a common baseline and diverging would have been to execute three independent aircraft development efforts. A lack of a common starting point (use of prior baselines) would not have produced beneficial commonality, as commonality does not arise by chance.

10) **The opportunity to create three similar variants (four if counting AA-1) in a sequential manner built a tremendous amount of experience within the team and learning through development of each model, although the incorporation of these learnings into the variant designs has been "directional." The "forward propagation" of changes has been more prevalent than "backward propagation" due to a combination of high switching costs and limited benefits associated with the latter. The net result has been the incorporation of learning into later variants and a decline in commonality.** The creation of three similar aircraft variants utilizing the same extended team provided the JSF organization with tremendous amounts of experience. Each variant was developed at a different time, based on the best understanding of the design and needs at that point in time. This experience has evolved with the program, with the most accurate state of

knowledge being the present state. The result has been the near continuous generation of potential changes that could impact any variant.

"Forward propagation," or the incorporation of learnings from an existing or past variant development effort into a future variant, has been prevalent across the program. Carrying an improved understanding of needs and design performance into a future development effort simply makes sense. Engineers start with a previous design as a baseline, and update this baseline to meet the needs of the new variant, resolving known issues in the prior design, etc. The cost of carrying learning forward is virtually non-existent from an NRE standpoint and carry-forward offers the potential recurring cost benefits of maintained commonality.

"Backward propagation," or the incorporation of new improvements from a current development effort into an already completed or more mature design, is much less prevalent: high switching costs combined with incremental benefits create little incentive for change. Retrofitting an existing design often entails paying dramatic step changes in cost due to elevated switching costs for tasks such as flight certification. While many designs from newer variants are technically feasible in the earlier variants, carrying improvements from later variants into existing variants has been held to a minimum due to the high retrofit costs and their highly disruptive nature. JSF is under great pressure in terms of development schedule and budget. Given the scale of the program, JSF could spend billions of dollars in design changes and as a result, management aims to eliminate these changes at all costs.

The relative ease of forward propagation of changes and difficulty of backward propagation of changes is driven by the sequential nature of JSF variant development and the resulting lifecycle offset as opposed to an underlying technical rationale. In this case, an offset between product lifecycles has limited commonality as opposed to an underlying performance impact. The incremental benefit of exact commonality makes sense when implemented from the start, but is difficult to justify as a change driver in an established, similar design.

11) **Part commonality metrics exist; are actively tracked by the JSF team; and are regularly presented to management and the customer. Initial commonality metrics were weight-based but are moving toward part number analyses (with costs) as design definition increases for each of the three variants.** The Affordability team tracks part commonality with a classification that includes fourteen combinations of unique, common, and cousin parts across the three variants (Figure 34). These metrics have been formally reviewed by the development team on a quarterly basis throughout SDD.

The commonality metrics are evolving as design maturity increases. Up until the April 2007 site visit, the majority of commonality data had been based on part weight estimates. These estimates represent the earliest available design information for the three variants, but do not address cost directly. Metrics are now shifting towards cost-based approaches as the designs mature.

		CTOL	STOVL	CV
1	Tri Common CTOL/STOVL/CV	Common	Common	Common
2	Dual Common CTOL/STOVL	Common	Common	N/A
3	Dual Common CTOL/CV	Common	N/A	Common
4	Dual Common STOVL/CV	N/A	Common	Common
5	Dual Common CTOL/STOVL – Cousin CV	Common	Common	Cousin
6	Dual Common CTOL/CV – Cousin STOVL	Common	Cousin	Common
7	Dual Common STOVL/CV – Cousin CTOL	Cousin	Common	Common
8	Tri Cousin CTOL/STOVL/CV	Cousin	Cousin	Cousin
9	Dual Cousin CTOL/STOVL	Cousin	Cousin	N/A
10	Dual Cousin CTOL/CV	Cousin	N/A	Cousin
11	Dual Cousin STOVL/CV	N/A	Cousin	Cousin
12	Unique CTOL	Unique	N/A	N/A
13	Unique STOVL	N/A	Unique	N/A
14	Unique CV	N/A	N/A	Unique

Figure 34: The JSF commonality matrix illustrates the complexity of tri-variant commonality. Fourteen combinations of unique, common, and cousin parts exist and are tracked by the team. (Graphic courtesy of Lockheed Martin. Used with permission.)

12) **The JSF commonality metrics do not account for software, although it represents a significant SDD expense.**

13) **The JSF software vision is to support all three variants with a common, configurable software baseline. This vision is enabled by the unique cost structure of software but hindered by a strong software dependence on the actual hardware configuration. Multiple baselines are currently being supported and will be supported for at least the next several years.** The JSF software is distributed across almost every system within the aircraft; is being developed through a large extended team that spans across approximately 50 global sites; and will consist of an estimated 22 million lines of code (U.S. Government Accountability Office, March 2007) when fully operational. The vision for this software is to produce and maintain one common software baseline that will support all three JSF variants.

    The opportunity to develop, produce, and support one baseline is relatively unique to software. Development is costly, just as in the case of hardware development. Production is almost free in comparison to hardware production. Additionally, installed but unused software has little to no impact on aircraft performance. Support costs scale with the number of fielded units but the scaling is much weaker than is the case for hardware support. The result is that fixed development costs dominate software development decisions. Software can address the superset of needs through the addition of new, configurable features to a common baseline. No "manufacturing" penalty results. The mechanical analog does not exist.

    The challenge with achieving the vision for a common baseline is the hardware dependence of the software systems and the need to support development testing of AA-1 and other test aircraft that reflect production of an evolving design. The various development programs require their own customized (and immediate) support, preventing a merger of the multiple baselines at this time.

14) **SWAT weight reductions were achieved through a "filing and grinding" approach that entailed elimination of weight from all possible locations within the STOVL design. A significant loss of part commonality resulted due to the need to correct the overoptimistic initial commonality level between the first CTOL and STOVL designs and a lack of incorporation (forward propagation) of these changes into the CTOL (optimized) and CV versions.** SWAT was required in order to save the JSF program. The team successfully achieved this goal through rethinking the entire STOVL design and removing weight wherever possible. Changes spanned the entire aircraft, creating a large number of changes, each one of which represented a potential deviation from commonality unless the modification was carried to the CTOL and CV designs.

    Commonality deteriorated for a number of reasons. First and foremost, the initial commonality expectation was too high given the variation in requirements: SWAT represented the need to undo excessive levels of commonality and the associated weight penalties in order to produce an acceptable design. Second, SWAT change implementation across the CTOL and CV variants was limited in many cases by the significant differences in the weight reduction thresholds (both Non-Recurring Engineering and recurring costs) between the three variants. Given the urgency around STOVL weight and saving the program, STOVL had very high development and recurring cost thresholds. The CTOL and CV variants had a lower willingness to pay for weight reduction. In these cases, divergence resulted due to economic factors rather than for reasons of technical infeasibility.

15) **The JSF team takes a true lifecycle view of affordability and has conducted extensive analysis of the penalties and benefits of commonality from this perspective.** While development cost savings in SDD were a strong enough incentive to pursue commonality, the team is aware that the lifecycle impacts of design decisions, including those made about commonality, will have a large impact on the lifecycle costs of the JSF program. The interviews uncovered examples of the consideration of commonality across every aspect of the program. Design and manufacturing were the most obvious examples but others exist. For example, training will be conducted in a common training center with approximately 80% of the training being a common core; 10-12% being similar training with service specific terminology; and 8-10% being truly unique[26]. Additionally, the innovative global logistics system ("Autonomic Logistics") will locate spares in common depots that may support multiple nations. Logistics is carefully considering the cost benefits of common components as one of many factors that impact the cost, response, and reliability of support.

16) **The SDD contract incentive structure and budget constraints focus Lockheed Martin's development decisions on the minimization of development and Unit Recurring Flyaway costs. While almost always evaluated during trade studies, Operations and Support costs, the largest expected subcategory of lifecycle costs, may be subordinate to nearer term expenses when difficult trades must be made.** Lockheed Martin and its extended team

[26] STOVL operation is an example of unique training, as this functionality is not applicable to the other variants.

must realize profits in each stage of the program. The SDD contract is structured to pay Lockheed Martin a one-time incentive based on producing a URF cost below the contract-specified threshold. When the program enters the production phase, payments will initially be received in a cost plus mode followed by fixed cost. A below target URF from SDD provides no recurring production benefit for Lockheed Martin.

Given very tight remaining SDD funds, the available development dollars must be invested in URF cost reduction opportunities as they provide a path to short term profitability. These investments may not necessarily be the best from the standpoint of Operations and Support. As stated previously, the team is clearly aware of lifecycle cost issues and has a major effort around Autonomic Logistics, but when tradeoffs between short term profitability and long term benefits arise, program funding continues to limit Lockheed Martin's ability to invest in changes with potential long term paybacks.

17) **As a systems integrator, Lockheed Martin must realize many of the benefits of commonality through transactions with its suppliers. Suppliers tend to be aware of the benefits of commonality; are motivated to pursue these benefits; and may not be willing to yield these benefits back to the prime. The latter point is compounded for single source situations.** The need to realize commonality benefits within the supply base is becoming increasingly important to Lockheed Martin: 81% percent of the total JSF materials costs are now purchased by Lockheed Martin in comparison to 60% for past programs. Realization of benefits becomes more difficult for cousin parts and systems that may have been quoted at different times. Supplier education and inclusion of commonality in contract negotiations is required to effectively leverage the benefits of commonality.

18) **Systems (mission and vehicle) have maintained a high level of commonality in comparison to the airframe. The reasons for this seem to be better alignment of capabilities across the three variants; lower performance driven weight impacts; and the fact that system development occurs across a transactional boundary.** There appear to be three reasons for higher commonality in systems rather than in the airframe. The first two, alignment of capabilities and lower weight (relative to the airframe), were commonly discussed during the interviews. The third reason, the fact that system development occurs external to Lockheed Martin, represents a seemingly significant but unrecognized reason for maintaining higher levels of commonality. Suppliers clearly delineate the costs of a change due to the transactional nature of the relationship with Lockheed Martin. The suppliers desire to make a profit from their investment in changes. From Lockheed Martin's perspective, these changes appear to have high costs relative to airframe changes, making Lockheed Martin less likely to pursue systems changes through the course of development due to their high costs. In effect, the high system switching costs maintain system commonality.

19) **The JSF program's approach to commonality relies on a strong system-based organization structure that has limited independent ownership of the individual variants and also limited formal ownership of the platform itself. The majority of the organization is organized by subsystem with each subsystem team owning its part of all three variants. Complementing this organization structure is a strong cultural emphasis on commonality**

rooted in the program vision and projected by the leadership team. The commonality culture has driven evaluation of commonality decisions to the lowest levels of the organization, the point at which commonality is either maintained or lost. An examination of the first few levels of the organization identified little in the way of roles or teams that support individual variants, with the exceptions being a Director of Air Vehicle Development, individual Airframe Leads, and Ship Captains.[27] The Director of Air Vehicle Development (Terry Harrell), was responsible for leading the transition of all three jets from preliminary design through layout and into detail design. Terry had overall design authority and was able to set commonality guidance as required. He realized that while commonality was important, it was not an end goal and as such, he did not push commonality where it did not occur naturally. Below Terry (in terms of the system hierarchy) were the individual Airframe Leads, responsible for development of the three airframes which from the beginning were believed to require significant amounts of specialization. The Airframe Leads collaborated during development, with the later leads understanding that they would receive the output of a prior airframe development effort. Ship Captains represent the most specialized position out of the three listed here: they were responsible for getting a specific production aircraft (e.g., BF-1) of a specific variant through the production process. The Ship Captain's role was to "lock-down" the design for a specific airplane in a way that balanced risk with new feature incorporation. Joint decisions were made between the Ship Captains and Air Vehicle Development Director regarding feature readiness for inclusion in a specific production aircraft. Risk had to be traded against the desire to test and certify newly developed (and required) features. A Ship Captain can cut some of the design improvements if necessary to meet schedule, although all changes should ideally be incorporated by the end of SDD to ensure that they are proven out as part of the program and incorporated into the baseline design. Being too conservative on the configurations would mean that features would be tested later than desired, while being too aggressive would add risk to the production build and test of a given aircraft. Given the tremendous pressure to build and test the first production units on time, Ship Captains had a lot of power in the organization, although the Air Vehicle Lead, retained ultimate design authority.

Outside of the above roles and supporting teams, the closest JSF came to having an individual product focus was during SWAT. At that time over 550 people were assigned specifically to the STOVL variant with the team being led by Art Sheridan. At that time Art and his team were responsible for one variant and had a focused mission that was successful in the end. While highly successful, the SWAT effort drove a significant amount of commonality out of the airframe, although much of the loss in commonality was believed to be necessary (i.e., beneficial).

The JSF team's culture complements the organization. Everyone interviewed was aware of the need to consider commonality in their decision making process. In the words of one subsystem lead, "Everyone understood the mission." Everyone also had a realistic view of commonality as a potential means to achieve affordability, as opposed to a goal to be

[27] Supporting teams are assumed to be assigned to each role.

blindly pursued. Commonality has the potential to impact URF (manufacturing costs), a metric that every subsystem manager drives towards his or her target. The source of the pervasive awareness of commonality consists of the deep commonality roots of the program; the fact that commonality is a lynchpin in the program's vision for affordability; and the program leadership's strong belief in commonality/similarity as useful tools.

20) **Strong formal process controls are utilized as a final "quality check" on the cost impacts of the organization's commonality decisions. Examples of formal controls include the Change Control Board and the 8-Square sheet.** While change control boards are the norm in product development, the degree to which senior leadership from both the development team and the Joint Program Office (JPO) are involved is impressive. Proposed changes are reviewed from the perspectives of technical merit and overall program impact. Both NRE and URF impact are carefully scrutinized.

    The evaluation process is aided by the 8-Square template that requires the lifecycle costs of a change to a common component to be considered *from the perspective of each variant*. Key estimates include weight and drag impacts across variants (performance checks), URF cost impact per pound, and lifecycle cost impact estimates. Examples of the latter include SDD development, production, operations and support (non-fuel), and fuel costs**.** Cost thresholds existed for NRE investment, URF impact, and lifecycle cost impact. NRE investment is tied directly to the SDD budget. URF impact represents the variable cost (manufacturing cost) and is also important because it is tied to the potential SDD bonus payment Lockheed Martin can receive if below a certain threshold. Lifecycle cost impact is important for Operations and Support. While the SDD contract did not include incentives for prospective reductions in Operations and Support costs, supportability criteria have been tracked by the team and reported to F-35 management. While Operations and Support costs are the largest subcategory of lifecycle cost, prospective savings are longer term (30 plus year lifecycle), heavily dependent on ground rules, and the least likely to be estimated with certainty.

21) **The tri-variant approach of the JSF program, combined with the overlapped nature of the variant development cycles significantly reduced the startup inertia associated with the latter two aircraft: the team was already staffed and experienced by the time the second and third (or second, third, and fourth if counting AA-1) ramps started (Figure 35).** The nature of the fighter aircraft business makes the first resource ramp nearly unavoidable: fighter aircraft are developed infrequently enough that the development workforce cannot typically be maintained in anticipation of future programs. In the case of the JSF program, the first ramp-up was severe. The team went from approximately 200 to 4,000 in the first year of SDD. The follow-on variant development efforts were able to leverage the already established team. The end result was the elimination of a significant portion of the startup inertia (and costs) associated with the prior programs.[28]

[28] I am indebted to Don Kinard for clearly explaining this concept.

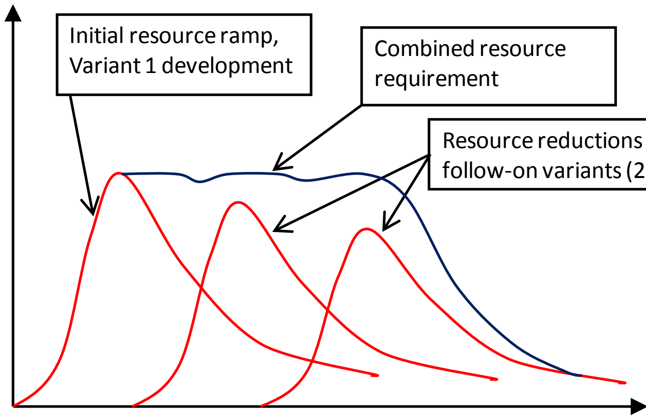

Figure 35: Illustrative resource loading profile for a tri-variant program illustrates initial ramp, followed by lack of significant resource ramps for Variants 2 and 3. (Don Kinard kindly explained this concept.)

22) **The Joint Program Office (JPO) is tasked with procuring a family of aircraft and is effectively representing the needs of a large fleet buyer. The JPO structure has served to link the needs of multiple "market segments" and has driven requirements compromise on the customer side. Strong support of commonality from the customer side is somewhat unusual.**[29] The tri-variant program and interest in commonality has been driven by the U.S. Government's policy of procuring joint systems when possible. This approach drives the services to compromise on their individual requirements, pulling requirements sets closer together wherever possible. Given that the U.S. Government is funding the majority of development and placing a significant portion of JSF orders, it stands to realize strong benefits from commonality and other affordability strategies. The result is a strong alignment between lifecycle decisions that provides net benefits in the development, production, operations, and support of all three variants. A penalty in one variant that produces a net benefit from the product family perspective is beneficial to the U.S. Government. This is often not the case with other systems. For example, if a customer operates only one model of a commercial aircraft family, the customer does not see benefits in common training, logistics, and repair processes that may be enabled by high commonality across the aircraft family. Only a mixed fleet operator sees these benefits.

23) **The portions of JSF development costs attributable to each variant are not known and could not be accurately tracked, a recurring theme within overlapped development efforts. Separation of costs by variant is nearly impossible in these situations due to the high degree of cross-coupling (e.g., resource sharing) between variants.** NRE costs have declined from AA-1 to STOVL to CTOL (optimized) to CV, but the magnitude of these costs is not known with any precision. The overlap in development combined with high degrees of common development do not allow for accurate separation of costs. While exact high level cost savings by program are unknown, lower level metrics all indicate increases in design efficiency when considering the three (or four) aircraft development efforts. The number of new drawings per variant has gone down, as have the average hours invested in each part

[29] Examples exist in the airline industry, although the customer base is much larger; the needs are more diverse; and no single customer dominates to the extent that the U.S. Government drives JSF requirements.

design. More importantly, the total development savings is known for the product family: 3 variants are being procured for the cost of approximately 1.8.

4.4. Brief Summaries of Cases C through G

The public reports for Cases C through G are located in the Appendix of this dissertation. The reader is encouraged to review these reports as each provides unique insights into the development of complex product families. Very brief summaries are provided here.

4.4.1. Case C: Commercial Aircraft

Case C examined the development and current status of a highly successful commercial aircraft family. The development program was aimed at making a broad range of incremental improvements to an existing aircraft family. Four of the variants are discussed in the public version of the case report (Appendix) and are referred to as "Small," "Medium," "Large," and "Extra Large" to indicate typical passenger capacities (Figure 36). It is important to note that all variants in the family are not covered in the case study report.

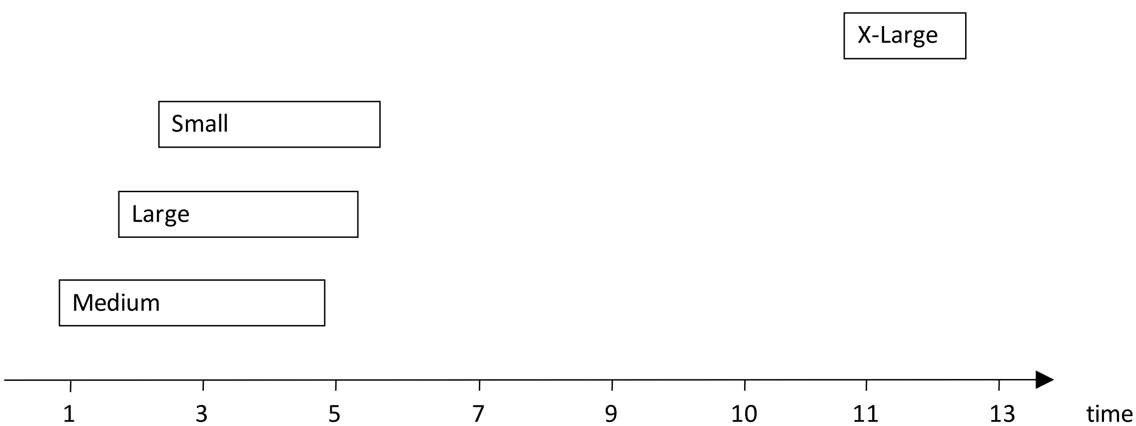

Figure 36: Initial three commercial aircraft models of Company C and an unplanned derivative. The latter was highly successful in the marketplace. Bars indicate the time period from program launch to flight certification.

The initial product family vision for called for the development of three aircraft variants having various ranges and passenger capacities. The three variants were developed in a sequential overlapping manner due to resource limitations. Development started with the Medium variant due to the existence of significant early customer orders. Development of the Medium variant was followed by the Large variant and then the Small variant. The initial vision had high conceptual levels of commonality including a common fuselage architecture that could be stretched and shrunk by using different size "donuts;" a similar wing architecture; a common engine with adjustable maximum thrust; and common tooling. Opportunities for design commonality were considered during development, but were often rejected due to the negative impact that commonality (and the associated weight increase) had on direct operating costs, a critical attribute from the customer perspective. The outcome: high degrees of design similarity and process commonality. Commonality was never a goal for Company C's product development efforts. It was a potential tool.

The Product C family was extended beyond the original three variant vision to include other aircraft. One of these models, the Extra Large variant, is discussed in the case study report. This model extended passenger counts into a range that was explicitly excluded in the original product family vision. Common tooling was an end goal of the Extra Large variant development program, while designs were optimized as required to create a successful product. A significant number of design changes were made and these changes spanned across the entire aircraft. The aircraft was highly successful in the marketplace and is noteworthy for the purposes of this research because it was specifically excluded from the initial product family vision.

4.4.2. Case D: Business Jets

Case D examined the development history of Company D's most recent in-production aircraft and their predecessors. At the time of the study, the product family consisted of four models, V3.1, V3.2, V3.3, and V3.4 along with their immediate predecessors, the V1 and V2. For the purposes of the case study, the history was classified into three phases which are illustrated in Figure 37. Phase 1 represents the earliest product models, culminating with development and production of the first business jet within the scope of this study, V1. During this time, the company designed and produced only one aircraft model at any given point in time. New, more capable models replaced existing models. Phase 2, consists of the V2 program and represents a shift from production of a single aircraft model to production of multiple models, the V1 and V2. Phase 3 entailed a shift to development with a product family awareness. The aircraft grouped into Phase 3 are the V3.1, V3.2, V3.3, and V3.4. Product models were developed sequentially, with the exception being the minor revisions made to the V3.1 and V3.2 to produce the V3.3 and V3.4, respectively. Product development has been primarily focused on reusing prior products as baselines as opposed to the creation of Intended Common elements.

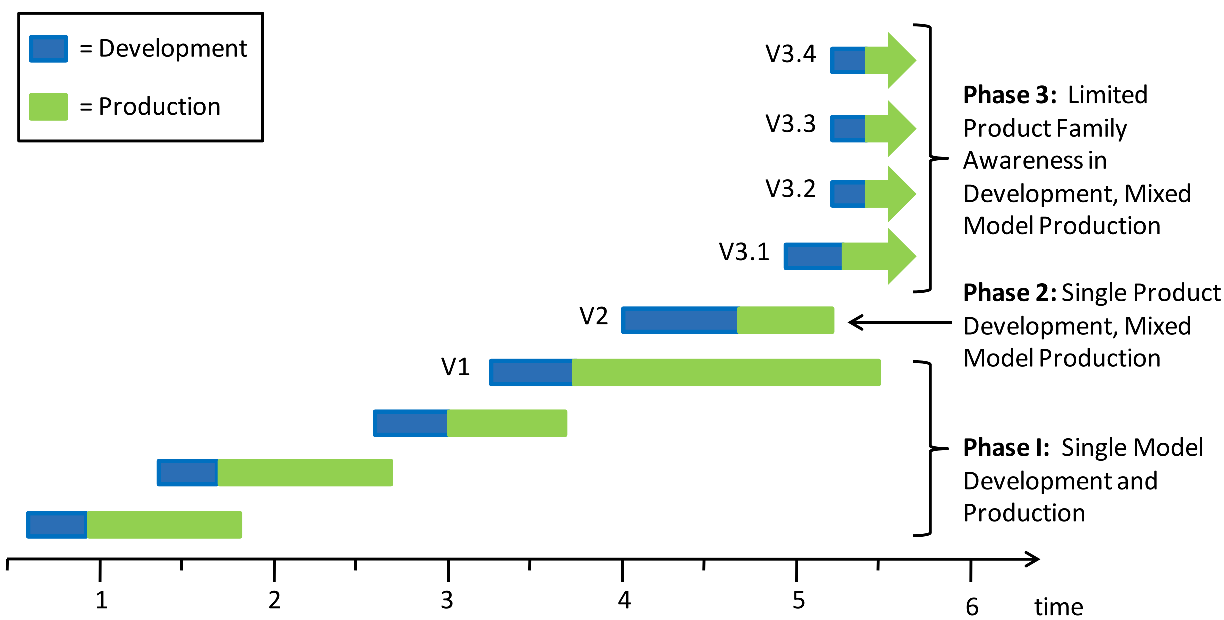

Figure 37: Company D's product history illustrates a shift from single product development and manufacturing toward multi-product development and manufacturing.

The development of the V2 aircraft presents a good example of the evolution of commonality at Company D and within product families in general. The V2 design was initially anticipated to be highly common with the V1 design but multiple design iterations and strong customer feedback drove significant, required design changes that significantly reduced commonality between V1 and V2. One interviewee estimated that the initial V1 and V2 designs were roughly 95% common, while the final V2 design was closer to 20% common.

More recently, commonality has become increasingly important to Company D as the company has added more product models. As an example, development of the V3.1 was conducted with a vision for the V3.2 product, potentially allowing for commonality to be exploited to a greater degree than it had been in the past. The V3.1 program was aware of the need to develop a follow-on variant and could potentially have made design decisions that supported this future need. The team's greatest success in this area was the development and implementation of a common cockpit which provides pilot training and maintenance cost reductions to customers and development and manufacturing cost reductions to Company D. As an example of rejected commonality, performance compromises were not accepted in the V3.1 airframe design in order to enable future commonality with the V3.2. Instead, the V3.2 utilized the V3.1 as a design baseline from which to make required modifications.

4.4.3. Case E: Printing Presses (Commercial)

Company E's printing press portfolio consists of three product lines (Figure 38). Product Line 1 ("PL1") systems print on sheets of paper. Product Line 2 ("PL2") systems print on rolls of alternative materials. Product Line 3 ("PL3") systems print on rolls of paper. As with Company C, the initial vision for products did not (and could not) encompass all future product models.

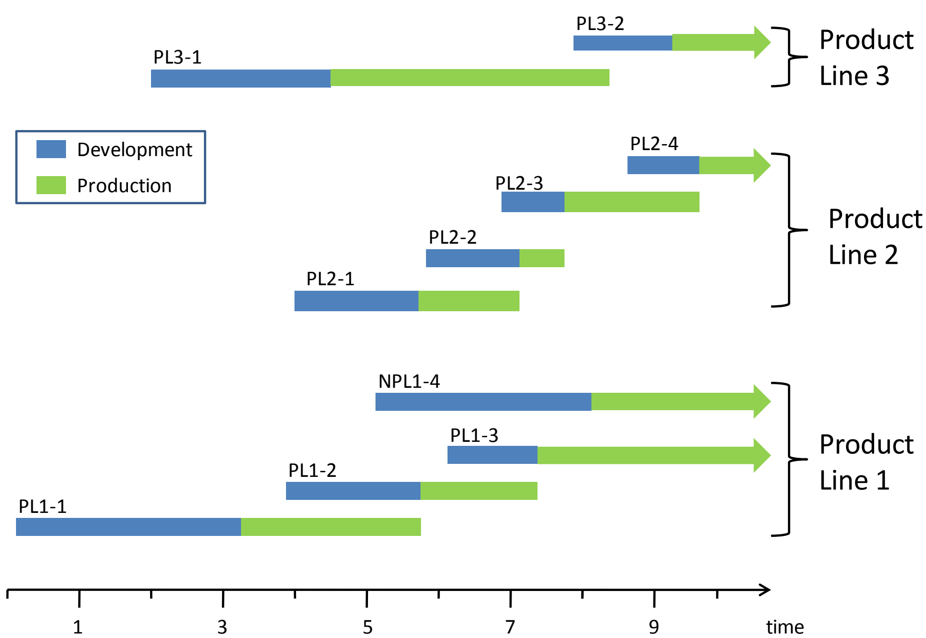

Figure 38: Case E product family history. Bars represent approximate development start, first shipment, and last shipment. Within a given segment (e.g., Product Line 1), new models replace prior models with the one exception being overlap between production of the PL1-3 and NPL1-4 models.

Company E's approach to new product development has been centered on the development of a new core printing technology, followed by deployment of this technology into multiple market segments in order to leverage the initial investment and in order to achieve the cost, lead time, and risk benefits of reuse. The company heavily leverages its printing technology, software, and control system components, all of which represent large investments. Given that volumes are highest in Product Line 1, this line typically serves as the lead variant for a new printing technology, software system, or major new feature. The other two product lines then combine the applicable Product Line 1 innovations with Product Line 2-specific or Product Line 3-specific advancements to address the needs of the other market segments. Products have been developed in a sequential overlapping manner and have utilized prior product baselines. Limited pursuit of Intended Common elements has been conducted with exceptions being the underlying technology, software, control system components, and printing supplies. Commonality is not actively tracked and managed at Company E.

4.4.4. Case F: Communications Satellites

Case F examined a platform-based series of communications satellites. The scope of the study consisted of examining fourteen satellites that either had already been launched or that were well-along in the development process. These satellites were based on an evolving bus, or platform, that was and is intended to support multiple spacecraft designs. (See Figure 39.)

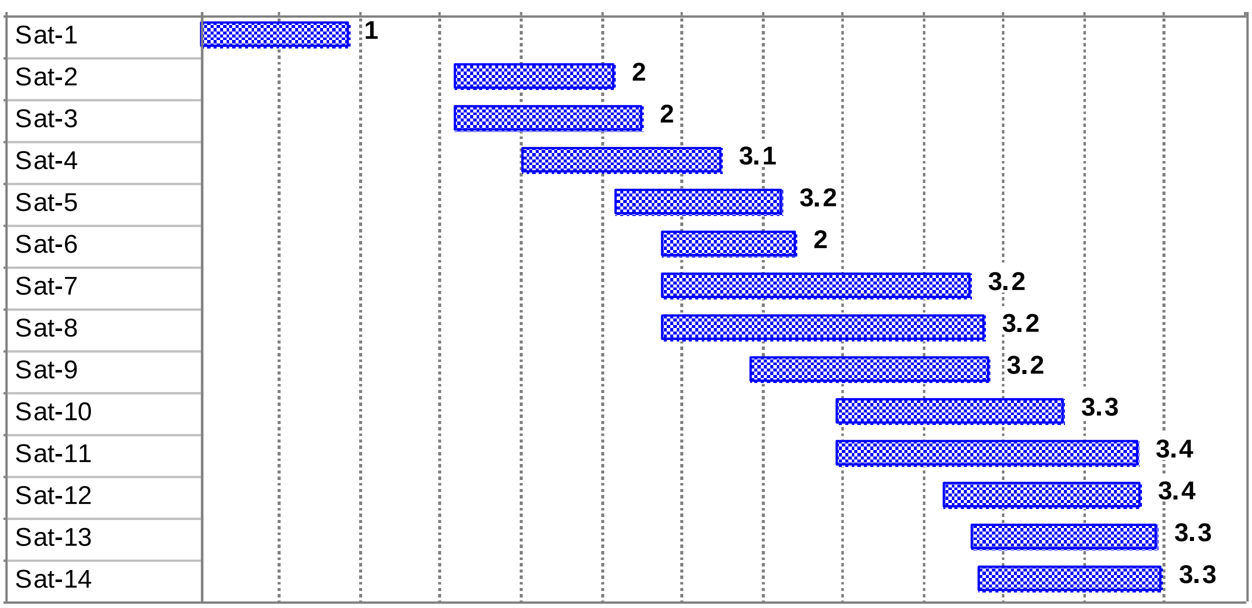

Figure 39: Satellites within the study's scope, including platform (bus) type designation (at right of each bar). The bars indicate the period of time from initial order to launch date. The horizontal axis is time. Dates have been removed to preserve case anonymity.

The initial platform vision was to create a scalable platform that had three distinct configurations. Each configuration would enable Company F to provide customers with varying degrees of capability (power) while reducing development costs, production costs, and product lead times. Development of the platform was, for the most part, incorporated into a single satellite program (Sat-4).

As illustrated in the case study report, Company F made significant and repeated investments in the underlying bus for a number of reasons. First, the company was small and had limited resources at the time of initial bus development. Second, the company had limited visibility into future sales, meaning that future revenue was uncertain. Third, the satellite market was in a period of transition and the market requirements for the class of satellites produced by Company F were highly uncertain. Fourth, the company's culture was primarily focused on executing individual satellite programs. The combination of these factors limited Company F's ability and willingness to invest in full development of a scalable bus during the first development iteration. As a result of these factors, development of the platform evolved with each satellite order that required capabilities beyond those that could be supported by the existing bus design. As with the other case studies, product development proceeded in a mostly sequential manner and relied heavily on the reuse of prior product baselines. Evidence of formal platform management was limited.

4.4.5. Case G: Semiconductor Manufacturing Equipment

The Company G case study examined the development history and current status of Company G's implanter products, a type of semiconductor manufacturing equipment (also referred to as "semiconductor capital equipment"). The study focused on the company's highest volume product lines: High Current and Medium Current (Figure 40). The product lines were based on a platform strategy that utilize common and similar elements to provide common supporting functions across all products. Examples of platform elements included the control system; positioning system; wafer environment and handling system; and beam architecture. The platform was utilized for every production system that Company G shipped as of the time of the case study.

Like the other companies, Company G historically followed an approach to commonality that was focused on reuse as opposed to development of Intended Common elements. Each product relied heavily on a prior product baseline, with modification to meet new requirements. Even in the case of the underlying platform, modifications were made to the prior platform version as required to meet the needs of the new product and its associated market segment. The result was a significant loss of commonality that was attributed to meeting market needs and to mostly informal management of the platform. (Two exceptions are described in the next paragraph.) The relative importance of each of these factors could not be determined during the case study.

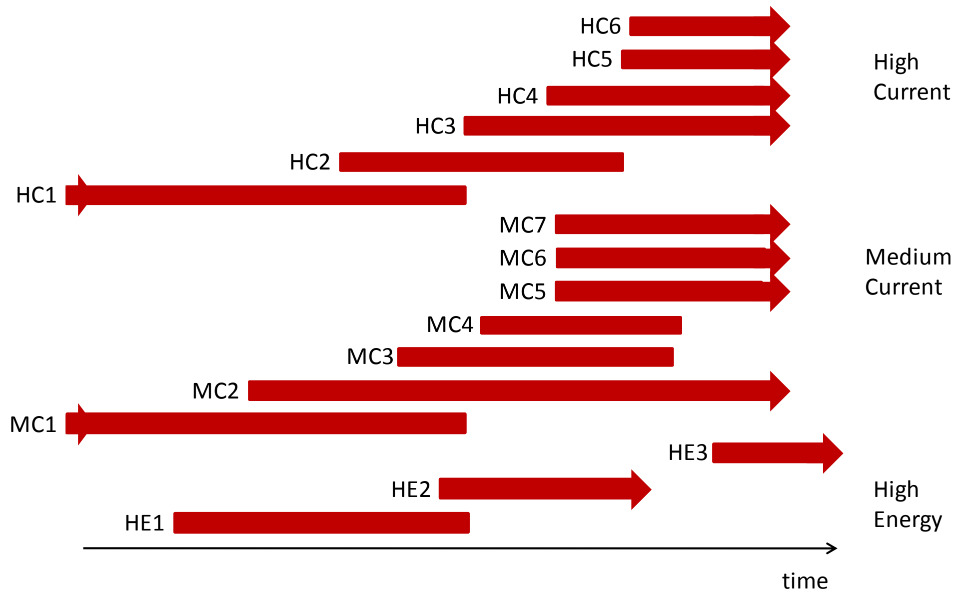

Figure 40: Company G's platform-derived product history. Bars illustrate approximate start of development and end of production for each product. The split between the two was removed due to proprietary concerns.

Company G provided two noteworthy exceptions to the general “sequential development and reuse of prior product baselines” description of the case studies. The first was the intentional development of a common building block, the software control system. The software system was developed outside of a product development program; was intended to be common; and has maintained very high levels of commonality. Approximately 95% of the software code is common to all products and code revisions in support of new products require between 10% and 25% of the investment in the initial software baseline. Second, three of Company G’s products were developed with the explicit intent of sharing high levels of components while addressing different price points in the market. The three products have been highly successful in the marketplace and have high degrees of commonality (greater than 80% of material costs).

4.5. Main Findings from the Seven Case Studies

The cross-case findings are reported in three places within this dissertation. First, high level findings are presented below. A composite description of platform-based development (based on the case studies) is presented followed by the findings which are divided into the following five categories: changes in commonality over time, lifecycle offsets, economic benefits and penalties, the influence of management actions, and additional findings. The “additional findings” category is utilized to provide several interesting findings that were not directly related to the original field research questions. The categories are not mutually exclusive and in cases of overlap, findings have been listed under the most relevant category. Second, the in-depth findings specific to divergence are discussed in Chapter 5. Third, findings related to lifecycle offsets are reported in Chapter 6. Some repetition exists between the findings reported in this chapter and the discussions of Chapter 5 and Chapter 6, although attempts were made to limit specific detail discussions to one location.

Above all else, the case studies clarified the extreme complexity that arises from pursuing commonality within the context of complex product families. An already complex endeavor, that of developing a single product, is made more complex through the decision to pursue platform-based development. Uncertainties associated with the market, technologies, and internal design and process knowledge are all compounded by the need to make decisions that impact more than one product.

4.5.1. Platform-Based Product Family Development in Complex Product Families: A Description Based on the Cases

While the case studies came from various industries and companies, a surprising degree of similarity existed between the companies' approaches to platform-based development of their complex product families. The following description is essentially a composite of the product family development approaches of the seven case studies, with key areas of difference emphasized. While many of the elements of this description are listed as later findings, the overall description is believed to provide a valuable high level summary of many of the key case findings.

All but one of the product family histories began with an initial vision for a number of product variants[30]; the markets the variants would serve; and some level of understanding of the individual variant characteristics or designs. The extent to which the individual variants were developed in parallel varied considerably across the case studies. At one end of the spectrum (e.g., Cases E, F, and G) were market analyses with very limited design investment being made to understand the supporting products. At the other end of the spectrum was Case B, the military aircraft case. In this case, extensive development effort was undertaken over the course of approximately seven years; effort that included the parallel development and testing of actual flight demonstrators of prototype versions of each variant. From the standpoint of commonality, the product family vision tended to have the highest level of optimism with regards to the degree of commonality. Information was limited; commonality was of interest to executive management; and optimism ran high.

While the degree of investment in product family vision creation and early product family concepts varied considerably across the cases, each of the cases reached a point at which parallel development was no longer feasible. Once this point was reached, development of each of the product variants proceeded in a sequential (non-overlapping or overlapping) manner, an outcome mandated primarily by the need to balance resource requirements.

The start of sequential development, regardless of the state of the product family vision, represented a significant transition in the history of each of the product families. At that point in time, emphasis shifted from the development of a product family with commonality to development of the lead product. Resources (both people and investment) were focused on development of the individual product, an extremely complex undertaking in the realm of complex products such as those studied within this research program. Incentives were aligned

[30] One exception was identified: the early history of the business aircraft company (Case D) was focused on creating one product at a time.

with the creation of individual products. Limited to no input was received during lead variant development with respect to the needs of the other variants; an outcome driven by a lack of resources, understanding, and uncertainty. The result was a lack of ability and/or willingness to act on the needs of the future variants at the expense of the more immediate and certain needs of the lead variant.

The lead variant program had two goals, one of which was implicit. The first goal, that of creating the lead product, was well-understood and acted upon. This goal was both concrete and near term. The second goal, which was implicit, entailed the creation of the Intended Common elements; i.e., creation of the product platform. These elements were almost always owned by the program manager who was charged with development of the lead variant (the military aircraft case was the exception and the automotive case was a partial exception). The result of the lack of platform ownership combined with resource limitations and a lack of understanding of future product needs led to a skewing of the underlying platform design toward the needs of the lead variant.

After development of the lead variant, the organization turned its attention to development of a follow-on variant. The lead variant was utilized as a baseline design which was reused in an informal manner. The resource constraints of the organization provided incentives for reusing previously developed product elements although requirements changes (market and internal); the availability of new technologies; and learning from prior products often produced incentives for change. From the perspective of the follow-on variant, little to no differentiation was made between elements that originally had been developed as Intended Common or Intended Unique: all prior development simply represented a “parts bin” that could be leveraged to reduce the development cost, lead time, and risk of the follow-on variant(s). As was the case with lead variant development, follow-on variant development had little involvement from the previously developed product team (the lead variant) or from future planned derivatives. Existing components were adapted to meet the needs of the current program and commonality was reduced. Reductions occurred for both beneficial and non-beneficial reasons.

The following sections build upon some of the key elements of the above description and also add key findings that were not addressed in this overview.

4.5.2. Findings Related to Changes in Commonality over Time

Prior to the case study research, an initial hypothesis had been created about changing commonality: commonality declines with time (i.e., divergence occurs) and this decline in commonality lowers the profitability of a product family. The case studies were approached with this hypothesis in mind, while looking for counter examples. Strong evidence was identified in support of the divergence hypothesis and in refutation of the alternative, that of increasing commonality over time. Mixed evidence was obtained with respect to the second idea in the hypothesis, that of reduced profitability. The evidence suggested that a decline in commonality may have a positive or negative effect on profitability at the product family level.

Several key findings are listed here. Chapter 5 contains a deeper discussion and presentation of the case study evidence.

Finding D1: Common assets, such as parts and processes, become similar and unique assets over time. (Divergence occurs.) "Everything" looks common early in a program when little information is known about market requirements; technologies; and supporting product designs. (Discussed at length in Chapter 5.)

Finding D2: Losses of commonality may be either beneficial or non-beneficial. The loss of commonality is not a negative in and of itself. Beneficial divergence results in a net increase in product family profitability. Drivers of beneficial divergence include opportunities for increased revenue and cost reductions associated with the elimination of commonality. An example of the latter is the elimination of an excess capability penalty that is not outweighed by the benefits of scale, learning, and reduced development. Non-beneficial divergence results in a net decrease in product family profitability. Drivers of non-beneficial divergence include a lack of a product family perspective in decision making and, potentially, a lack of management controls. (Discussed at length in Chapter 5.)

Finding D3: Similarity, or commonality at lower levels than the original decision making reference frame, offers the benefits of common processes and potentially learning curve effects without the hard constraints of exact replication and the associated penalties these constraints place on product performance and other product attributes. Similarity is complementary to the default development approach of utilizing an existing product or products as a baseline and modifying this baseline as needed to meet new requirements. Technology leverage was a consistent example of similarity, with an excellent example being the printing press company's use of a given printing technology across many products. An additional example comes from the military aircraft program which has experienced reduced development hours for similar parts associated with later aircraft variants.

Finding D4: Platforms are dynamic, rather than static entities. Each change to a common element represents the *potential* loss of commonality. Sources of change consist of changing requirements, learning, availability of new technology, and component obsolescence. The case reports consistently demonstrate the dynamic nature of platforms. For example, the communications satellite development programs almost always made significant revisions to the platform in support of new customer needs. (This topic is discussed at length in Chapter 5.)

Finding D5: Concerted efforts are required to establish or increase commonality as commonality does not arrive by chance. The cases provided two examples of concerted efforts: the formation of the initial product family plan and execution of separate building block development efforts. The product family plan represents an attempt to exploit commonality across the planned product family members and represents the highest planned or actual degree of intended commonality. Common building blocks (e.g., the semiconductor manufacturing equipment control system) also represent attempts to regain commonality. These efforts occur at the subassembly or component level. Both product family planning and common building block development represent concerted efforts to establish commonality.

4.5.3. Findings Related to Lifecycle Offsets

Finding O1: Product family development begins with parallel planning followed by a transition to sequential development of the individual variants. The point at which this transition occurs varied considerably across the cases. All seven companies created some level of product family vision prior to starting development of their more modern products. These visions entailed the anticipation of future models and at least some degree of analysis of what could be common across the product family members. Some of the visions were very high level; addressing potential market niches and high level performance specifications. Others involved significant investments in the conceptual design of multiple variants. In each case, the simultaneous development ended or significantly tapered off at some point, with development of a lead variant moving forward beyond that point.

Finding O2: Sequential development is driven primarily by resource limitations but is also influenced by factors such as market uncertainty and technological capability. Interviewees at each of the case study companies consistently emphasized the fact that parallel development was not an option due to resource limitations. As a result, offsets are introduced between development of the individual product family members. (See Chapter 6 for an in-depth description.)

Finding O3: Lifecycle offsets delay, reduce, and reapportion the potential benefits of commonality. Any potential benefits of commonality depend on the existence of a second product development program or second product. For example, development benefits cannot be realized until a second product enters development and the second product reuses components from the first product. Production also depends on the existence of a second product: benefits of shared economies of scale and accelerated learning do not occur until common elements are produced at production rates that are greater than any one product (scale and accelerated learning benefits) and/or at cumulative totals greater than anyone product (learning). Prior to the existence of a second product, a penalty may exist due to the costs of excess capability. The model and examples of Chapter 6 demonstrate the interplay between offsets and the cost benefits and penalties of commonality.

Given lifecycle offsets, the benefits of commonality may be reduced in comparison to the parallel development framework and they may be reapportioned between products. Lifecycle offsets reduce the benefits of shared economies of scale in production due to reduced degrees of overlap between two or more products. Lifecycle offsets reapportion the benefits of learning, favoring the follow-on variant. (Refer to Chapter 6 for additional detail.)

Finding O4: Offsets create a tension between commonality and innovation. The case studies made the constraining effect of commonality on innovation extremely clear. This trade was mentioned during multiple interviews at each of the seven case study sites. The concern was greatest at the printing press and semiconductor manufacturing equipment companies, both of which experience relatively high rates of innovation. Avoiding innovation in key customer differentiating features would quickly reduce a company's market share and/or revenues. Less well-discussed during the case study interviews was the potential for many areas of a high technology product to be relatively disconnected from customer critical features.

Finding O5: Limited Intended Common development occurs in practice due to uncertainty about future product needs and a lack of coordination across products. "Common building blocks" represent exceptions. The degree to which Intended Common development is pursued in industrial practice appears to be limited, an unexpected finding given the review of the platform development literature. Prior to the field research, the expectation was that product development programs actively invested in Intended Common development that supported future product creation; i.e., that penalties were incurred in anticipation of future benefits associated with commonality. The results of the field research suggest that this type of investment is limited.

The limited degree of Intended Common development appears to be due to uncertainty in the needs of future products and a lack of coordination across products. Uncertainty limits a company's willingness and ability to invest in Intended Common development. The uncertain needs of a future product are being traded against real, immediate needs of the current variant. Investment in a portfolio of commonality options that has an uncertain return was not a popular approach to development within the case companies. Beyond uncertainty lies a lack of coordination between individual product programs. A lack of coordination means that decisions are viewed from the independent product perspective, rather than the perspective of the product family. Given a lack of coordination, opportunities for commonality are not actively identified and implemented when beneficial.

Development of common building blocks represents a clear exception to the above statements. "Common building blocks" represent development of Intended Common elements; typically represent significant investments; and are managed outside the control of any individual product development program. Common building block development efforts were identified in several of the cases. For example, the business jet manufacturer developed a common avionics suite; the capital equipment company created common control software; and the printing company developed core printing technologies. These building block development efforts all required investments that were only justified from the perspective of multiple products. The efforts were funded and managed above the level of the individual product. Their ownership was independent of any individual product. In terms of planning, the previously mentioned parallel planning and preliminary design efforts associated with the product families (particularly the automotive and military aircraft examples) represent initial attempts to establish Intended Common components at the conceptual level.

Finding O6: In the context of sequential development, prior products serve as baselines for follow-on variants. Commonality is achieved through reuse of Intended Unique components, as well as any Intended Common components that may have been developed. A prior product is utilized as a baseline starting point from which to make modifications to produce the next variant. This common sense approach to development was pervasive in the case studies and leads to efficient resource utilization from the perspective of the current program. As an example, the truck model associated with the automotive case leveraged prior model year trucks and the SUV model that shared the new platform. Designs were either directly carried forward to the new model, or where adapted as required to meet new requirements. In the case of the satellite company, the company's programs leveraged the advancements in platform capability associated with each prior program, especially in the earlier years of satellite development and production. In an effort to minimize development cost, lead time, and risk,[31] the satellite program managers utilized prior programs as baselines and adapted the baseline designs accordingly. As an additional example, Company E's lower revenue printing systems leverage features created for the main product line.

Finding O7: In a sequential development setting, improvements to common elements that are identified as part of later variant programs are unlikely to be incorporated into existing products due to the high cost of their implementation. Companies avoid incorporation of changes into existing designs ("backward propagation" of change). Some companies, such as the military aircraft company explicitly avoided backward propagation, unless absolutely required to address a critical issue such as a performance or safety issue. They recognize the high costs and limited benefits of doing so. One interviewee from the military aircraft program stated that the program could have spent billions of dollars on backward propagation of change, had these types of changes not been actively prevented. The sequential nature of complex product development creates economic disincentives for implementation of changes; changes that may have been beneficial in a parallel setting. (The reader is reminded that parallel development appears to be nonexistent or rare in the complex product family domain, given the case evidence.)

Finding O8: Sequential development reduces the cost of learning by allowing learning to occur on one product and then to be leveraged by future products. Sequential development ensures that learning occurs on one product, rather than multiple products as would be the case in parallel development. Rather than addressing issues multiple times, they are addressed once. Each case demonstrated this concept, although the concept was most obvious in the military aircraft program which had tracked actual metrics such as the decline in labor for developing similar parts associated with later variants.

4.5.4. Findings Related to the Economic Benefits and Penalties of Commonality

Finding E1: The case studies indicated a lack of comprehensive evaluation of commonality opportunities. The lack of evaluation appears to be due to a lack of awareness of the need to evaluate opportunities for commonality and due to a lack of available evaluation methods and processes. The case studies illustrated a lack of analysis of the business case for commonality, with the most significant exception to this statement being the military aircraft program. Lack of awareness of the need for the analysis of commonality is directly connected to the single product mindsets that appear to form the basis of product development practice. In terms of evaluation methods and processes, the military aircraft and automotive cases provided the best examples, with other companies providing lesser evidence. Three of the seven case companies expressed interest in obtaining commonality analysis methods and tools. The simple economic model presented in Chapter 6 represents a small contribution in the way of analysis methods and tools.

[31] Risk is extremely important in the satellite industry, given that servicing a satellite is almost impossible, or at least cost prohibitive today. The result is that customers place a strong emphasis on heritage parts, or parts that have successful flight histories.

Finding E2: The data required to perform analyses of the benefits and penalties of commonality is limited. Attempts to analyze the linkage between program success and commonality proved to be very difficult during the case studies. Even when relevant data (e.g., investment and recurring cost data) exists, there is no credible basis for comparison. The success of a given strategy is known because the strategy is implemented and "tested" in the marketplace. Development costs, recurring costs, and revenues can be examined for a given product to determine overall profitability, but determination of the profit of the implemented strategy relative to another strategy that was not pursued is nearly impossible. The success of any alternative strategy is unknown with any degree of precision because the strategy was never pursued beyond a potential early estimate. (This finding extends far beyond the evaluation of commonality to any type of comparison between alternatives that were and were not pursued.)

Finding E3: Commonality has a potentially significant impact on revenue. While this finding is far from novel, the finding represents a consistent theme throughout the case studies. An awareness of the potentially negative impacts of commonality on product revenues was pervasive in industry and drove significant degrees of beneficial divergence. Knowledge of this relationship also may have driven avoidance of beneficial commonality, although this statement would need to be substantiated by additional research.

Finding E4: The benefits and penalties of commonality are asymmetric from the perspectives of individual product family members due to factors such as development order, relative production volumes, and relative capability differences. Development order influences the capabilities of Intended Common assets and establishes the potential benefits and penalties associated with reuse of these Intended Common assets in follow-on programs. Production volume differences drive differences in the relative shared economies of scale benefits realized by each variant, assuming some degree of overlap in production. As one example, refer back to Figure 22 (automotive example) which illustrates significant differences in the relative economies of scale benefits given significant production volume differences between two models. While the figure is conceptual, the automotive finance team estimated that the economies of scale benefit to the low volume product (SUV) was a 10% material cost reduction for common parts, while the benefit to the high volume vehicle (truck) was only a 1% reduction. The truck team sometimes found that the 1% reduction was more than outweighed by negative impacts on revenue. Relative capability differences also influence the benefits and penalties of commonality from the standpoint of a given variant. Assuming a need exists for both a high and low capability component or subsystem, one potential option is to create a high capability, common component for use on all variants. The variant requiring the low capability component may incur a cost penalty if development, learning curve, and scale benefits do not outweigh the cost of excess capability. In reality, the "high-low" scenario is over simplified. The case studies demonstrated that identification of a common design is rarely as simple as selecting the more capable independent design: each design likely has features that make the minimally acceptable common design a composite of two or more independent designs.

Finding E5: The potential development and recurring cost penalties of intended commonality are tangible and well-recognized within the case study companies. The penalties of commonality were consistently stated during the case study interviews. Development costs for a lead variant increase in relation to the independent alternative and a "commonality tax" (to use the term of the semiconductor capital equipment company) is paid in production of excessively capable components.

Finding E6: The benefits of intended commonality are less tangible than the penalties. The benefits of intended commonality are uncertain and delayed in the case of sequential development. Future development expenses may be reduced due to previously pursued intended commonality. Future production costs may be reduced for future products and, potentially, for the current product that implements an Intended Common design. The uncertain nature of future potential benefits was recognized by the case study interviewees as being a negative: the companies tended to focus on short term decision making and meeting immediate needs. In this environment, the benefits of commonality were less tangible in relation to the penalties.

The potential benefits of intended commonality appeared to be the most tangible within the military aircraft program. In this case, managers associated with development of the aircraft family were keenly aware of the potential development savings associated with reuse and the potential benefits of commonality in terms of recurring production costs. Managers did not blindly implement commonality; rather they were aware of the need to evaluate commonality as a potential aid in meeting their development targets. Through making a connection between commonality and costs, the perceived intangibility of benefits was greatly reduced.

Finding E7: Products with lower relative profits may have greater incentives to consider commonality, as this class of products often has lower relative production volumes and development budgets. The automotive, printing press, and semiconductor manufacturing equipment cases all highlighted the fact that higher profit products tend to receive the largest development budgets and tend to have the strongest incentives for design optimization. Products with smaller profit contributions have greater incentives to consider commonality. In terms of development, reuse of elements from the main product line provides a cost-effective way to perform product updates. The smaller development budgets allocated to these lower profit products can then be utilized to develop features that are specific to the lower profit product market segment. Within the case studies, the lower profit products were also produced at lower rates, meaning that these products realize larger relative benefits of shared economies of scale and accelerated learning. Given this situation, a given cost of excess capability is less penalizing for the lower volume product. Trades between scale, learning, and excess capability are examined in Chapter 6.

Finding E8: High development cost represents a mechanism that maintains commonality. Many of the case studies provided examples of the influence that high development costs have on commonality. The outcome is relatively straightforward: high costs of creating a replacement component encourage future reuse and increase the acceptable manufacturing penalty. The commercial aircraft engine was one such example: development of alternatives with different thrusts was cost prohibitive and drove reuse of the same engine. The impact of high development costs was most notable when the case company chose to integrate externally developed components into its product designs. The cost of changing this type of component is very clear because the changes occur across a transactional boundary. The change requestor pays a very clear price, unlike the less obvious cost of making changes to internally created designs. For example, the military aircraft program has maintained high levels of commonality in many of its externally developed systems (e.g., avionics): development of optimized alternatives was typically cost prohibitive, even during the SWAT period that was heavily focused on weight elimination. The value of making changes to these externally developed systems was not compelling relative to modifying internal designs.

4.5.5. Findings Related to the Influence of Managerial Actions on Commonality

"Managerial" is defined broadly here to include management, leadership, organization, and culture, the latter being heavily influenced by managerial actions.

Finding M1: Single product cultures, organization structures, and development processes are entrenched in complex product companies. With the exception of the military aircraft case and, to a lesser extent, the automotive case, the dominant approach to development has historically been one of independent development. Consideration of, and action upon, the product family decision making perspective was limited in Cases C through F. This is not to say that examples of the consideration of commonality could not be identified in each of these cases, but rather that this consideration appeared to be limited and informal in nature. While product family visions were created (e.g., communications satellites, printing presses, and commercial aircraft), development actions quickly shifted to development of individual products. Recent examples of increased awareness of the need to consider commonality were observed in all five of the cases that had longer product histories (Cases C through F). (Commonality was considered from the beginning in Case A and Case B.) For example, the business aircraft manufacturer pursued common avionics development in support of multiple aircraft models. Also, the semiconductor manufacturing equipment company created three products through an intentional commonality strategy.

The result of single product cultures, organization structures, and development processes is a lack of consideration of commonality across related products. Opportunities are neither evaluated nor identified in a consistent manner. While many opportunities for commonality may not produce net benefits, some certainly will and should be examined. All of the cases explored commonality opportunities to varying degrees, however, only one case, the military aircraft case routinely considered commonality between variants and the potential impact that a change to any one variant may have had on the product family as a whole. The automotive case was also an exception, although examination of opportunities for commonality was somewhat inconsistent: an organizational change part way through the program (between development of the first and second variants) resulted in the elimination of the platform team and at least a partial reversion to an independent program approach. (This situation has been rectified since the time of the case study.)

Finding M2: Commonality is typically managed in an informal manner. Common elements are not well-defined; formal ownership of commonality is rare; and process controls are

limited. Common components are not well-defined in practice. The product family vision specifies high level requirements for the members of the product family and may be supported by preliminary design work that investigates potential options for commonality. As development of the individual products progresses, the initial differentiation between common and unique components is lost. Logic leads one to believe that this ambiguity is likely to have negative implications for commonality and the realization of the potential benefits of commonality. The only clear example of commonality designation and tracking throughout development came from the military aircraft program. This program has tracked components from the conceptual design phase forward; utilizing the best available information.

Formal ownership of commonality was limited in the case studies. In Cases D, E, F, and G, the default owner of commonality was the first level executive that owned multiple products. Executives obviously have a broad range of responsibilities and do not have significant amounts of time to dedicate to the management of the common aspects of their product families. Case A provided the strongest example of formal platform ownership: a formal owner of common components (platform manager) existed until the platform team was dissolved prior to the development ramp of the second product. During the time that the platform team did exist, strong leadership and management processes were in place. The military aircraft case (Case B) represents a different type of exception: formal ownership of commonality was limited but appeared to be unnecessary because ownership had been driven to the lowest levels of the organization. The program did an excellent job with the evaluation of opportunities for commonality. Commonality has been infused into the corporate culture and appeared to depend less heavily on formal ownership.

Process controls were also limited in the majority of cases, with the military aircraft and automotive cases providing exceptions. In the case of the military aircraft program, any change decision was examined from the perspective of all three variants, *regardless of whether or not a change was directly being implemented on a given variant*. The decision was discussed as part of a change control board meeting which acted more as a final quality check rather than a mechanism for truly managing commonality.

Finding M3: The cases suggest three levels of maturity in terms of organizational approaches to commonality. At the first level is informal reuse of previously developed components. Ownership of commonality is non-existent, as are management processes and a general cultural awareness of commonality as a potential tool. A second level involves formalized ownership and processes that are utilized to ensure identification, evaluation, and implementation of commonality opportunities. In some cases, this level may include overly ambitious attempts to implement commonality "for commonality's sake." Strong managerial and process controls may be required to effect a change in an organization that is focused on individual products, as was the case in the automotive product family. The military aircraft program may indicate a third, more advanced level. In this third level, ownership of commonality and formal processes become less important as the need to consider commonality becomes engrained in the corporate culture. Commonality becomes one of many potential tools that may be utilized to improve product development outcomes. Further research would be required to confirm this three level framework, especially the observation that a "commonality culture" may be a more effective approach than formal management techniques.

Finding M4: Program managers who are responsible for an individual product variant are also typically the default owner of commonality. The "platform" is skewed towards the needs of the current program at the potential expense of compatibility with past and future variants. The likelihood of implementing and maintaining beneficial commonality declines. This situation arises due to the sequential nature of complex product family development; the lack of formal ownership and management of common elements; and single program cultures. In all seven cases, the underlying platform was developed as part of the lead variant development effort and was almost always managed by the program manager for the lead variant. The result was a skewing of the platform toward the needs of the first variant at the expense of fit with the needs of future variants. With each new variant development effort, ownership of the platform is passed to the program manager for the current product under development. Modifications (and their associated investments) are made as required to meet the needs of the current program.

Finding M5: Program managers approach existing products as starting points (baselines) from which to reuse and modify as required. They do not differentiate between Intended Common and Intended Unique elements. Once developed, a product represents a collection of previously developed assets. A development program manager selects relevant components from this collection when the fit with the needs of the new product is acceptable. The original development intent is irrelevant to the current program manager.

Finding M6: Functional organizations have incentives (such as work load or cost reductions) to pursue commonality but these organizations are often subordinate to the independent development programs that they support. Organizations with a strong emphasis on individual programs drive functional teams toward local design optimization and, therefore, away from commonality. This finding repeats prior comments made by Sanderson (1991) regarding the inability of autonomous teams to support overarching projects that go beyond the needs of an individual product.

4.5.6. Additional Findings

Finding A1: Evidence of the measurement and reporting of commonality was limited in the case study programs. Cases A, B, and C all had some degree of measurement and reporting with Case B being the most formal and sophisticated in terms of its designations.[32] (Refer to Figure 34 within this chapter for an example of the designations tracked by Company B.) The value of tracking is unclear as commonality levels do not have direct links to profitability or other high level program goals such as lead time and risk. Stated another way, attempting to maximize or minimize an overall commonality metric is risky at best. Commonality clearly

[32] Observed metrics were based on percentage of common/similar/unique parts or an attribute of common/similar/unique parts, such as weight. More complex metrics, such as those discussed by Thevenot and Simpson (2006), were not identified during the case studies.

offers benefits in certain situations, but not necessarily on a global scale as would be tracked by a metric.

Finding A2: Definitions of commonality vary significantly, by organization function. Different functions within the organization tend to focus on different aspects of commonality. Consider the example of the printing press case (Case E). Process Research and Development reported benefits from basic process carryover, and therefore emphasized this aspect of commonality. From the perspective of Process Research and Development, Company E's products were highly common. At the other end of the spectrum was Manufacturing, which tended to define commonality based on part number designations. Manufacturing complexity is partially driven by the number of unique part numbers associated with each product. Common part numbers enable common assembly and test and may reduce inventory costs.[33] Manufacturing tended to view the products as being much less common.

Finding A3: Customer and manufacturer incentives for commonality are not necessarily aligned. Conflict resolution depends on the degree of influence a customer has on the manufacturer. Conflicts may arise through different perspectives on commonality. For example, semiconductor fabrication facilities ("fabs") purchase equipment from multiple companies. This equipment often contains OEM subsystems with common functionality, such as mass flow controllers for gas delivery and vacuum pumps. In many cases, the semiconductor fabricator makes a fab-wide decision to use a certain brand of subsystem which equipment manufacturers are then forced to support. The fab benefits from commonality in operations through purchasing leverage (larger order quantities), reduced inventories, and reduced maintenance costs. The equipment supplier must maintain increased diversity in its product line due to the need to support multiple customers, each of which makes its component selection decisions in an independent manner. As a second example of conflicting interests, consider that a customer may plan to operate single or multiple product family members. The number and relative mix of the product family members, combined with the manufacturer's pricing decisions may significantly alter the benefits and penalties of commonality as perceived by the customer. For example, a single aircraft model operator has little direct incentive to accept commonality beyond the indirect benefit from cost savings that the manufacturer decides to pass on. The customer likely faces a real operating cost penalty.

While the benefits and penalties of commonality may be different from the perspectives of the manufacturer and customer, the degree of customer influence ultimately contributes to the decisions a manufacturer makes about product development, commonality included. The seven cases had widely varying degrees of customer influence. The military aircraft program had one dominant customer, the United States Government. Each satellite program had one specific customer and high levels of customization in order to meet this customer's needs. The semiconductor manufacturing equipment company had three or four highly influential customers that had significant influence on product development decisions. At the other end

[33] The caveat here is that an inventory cost reduction for a common part depends on the quantity of a given part number and the cost of each unit. If the total quantity cannot be reduced and/or the cost of the common component is higher than the independent component it replaces, inventory costs may rise.

of the spectrum was the automotive program which had a nearly countless number of customers. In this case, individual customers had much less influence over the company's design decisions, which were based more on the aggregate needs of the market.

The following table contains a summary of several key aspects of the seven cases.

Table 5: Summary aspects of the seven case studies.

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Product Type	Automotive	Military Aircraft	Commercial Aircraft	Business Jets	Printing Presses	Communications Satellites	Semiconductor Manufacturing Equipment
Initial vision for commonality?	Yes	Yes	Yes	Limited, but increasing	Yes	Yes	Mixed
Pursuit of Intended Common development?	Yes	Yes	Yes	Historical: No Current: Yes	Historical: Mixed Current: increased emphasis on Intended Common	Mixed	Mixed
Sequential vs. Parallel Development	Sequential; reuse from prior baseline. Driven by resource constraints and model year offsets. Early conceptual development conducted in parallel.	Sequential; reuse from prior baseline. Driven by resource constraints. Significant conceptual development conducted in parallel.	Sequential; reuse from prior baseline. Driven by resource constraints. Early conceptual development conducted in parallel.	Sequential; reuse from prior baseline. Driven by resource constraints; market evolution	Sequential; reuse from prior baseline. Driven by resource constraints and market uncertainty.	Historical: Sequential; reuse from prior baseline. Driven by resource limitations. Current: Some parallelism due to increased order volumes.	Historical: Sequential; reuse from prior baseline. Recent programs have increasing parallelism. Resources have increased, market has matured.
Lead Variant Characteristics	Lower production volume and total revenue. Decision driven by model introduction timing.	Higher production volume, lower complexity. Decision driven by complexity.	Led w/mid-range (capability) variant. Decision driven by customer commitments.	Increasing customer capabilities over early history; more recent history has led with high capability variant.	High production volume and total revenue.	Historical: Low capability first due to technical limitations.	Low capability first in a given product line due to technical limitations of rapidly evolving technologies. Development of common, new features often in highest production volume and revenue products first.
Strictly increasing internal requirements placed on variants?	No	No	No	No	No	No	No

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Product type	Automotive	Military Aircraft	Commercial Aircraft	Business Jets	Printing Presses	Communications Satellites	Semiconductor Manufacturing Equipment
Formal owner of commonality?	Yes, owner and supporting team but eliminated prior to completion of all variants.	Onwership driven to lowest levels of the organization.	Yes for preliminary design; then executive level default owernship.	Executive level (one of many responsibilities)	Executive level (one of many responsibilities)	Executive level (one of many responsibilities)	Executive level (one of many responsibilities)
Formal analysis of commonality opportunities? (e.g., business case for product family and lower level parts)	Limited. Early conceptual analysis of development and production impacts.	Yes. Lifecycle analysis conducted from product family perspective for a change to any variant.	Mixed. Strong analysis of weight and operating cost trades. Evidence of broad analyses was limited.	Mixed. Strong analysis of weight and operating cost trades. Evidence of broad analyses was limited.	Limited formal analysis although strong awareness of lifecycle implications of commonality in consumables.	Limited beyond initial platform plan.	Limited.
Formal management processes for commonality?	Early in program: Strong management through coordination meetings, joint design. Later in program: informal management after platform team was disbanded. Commonality levels reported at key program milestones.	Yes. Impacts of changes examined during development and "quality checked" through lifecycle cost impact report submitted to change control board. Also, commonality levels are tracked and reported.	Commonality levels are tracked for each product family model, with stability being maintained in common parts.	None identified.	Limited evidence of formal controls. Change control board meetings include representatives from all product lines.	Limited evidence. Product family vision was documented but action in support of the vision was unclear.	Limited.
Awareness of potential reuse benefits?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Culture	Single product mentality. This program represented the start of a cultural shift.	Very strong awareness of commonality as a potential tool for reducing development and recurring costs. This awareness was pervasive at all levels of the organization.	Single product focus in design. Strong awareness of the need for common manufacturing processes.	Single product, transitioning to multi-product. Focus on customer benefits of commonality.	Single product, transitioning to multi-product. Strong awareness of the need to maintain commonality in consumables.	Single product with attempts to develop core building blocks (bus).	Single product but shifting to multi-product and common building block development.

4.6. Chapter Summary

This chapter has provided examples and summaries of case study reports along with key findings that resulted from the cross-case analysis. The two full case study reports (cases A and B) were included in order to provide some of the rich context from which the cross-case findings were obtained. The findings from the seven cases have provided insights into platform-based development in complex product families. These findings have also suggested that the benefits, penalties, and implementation challenges associated with pursuing platform-based development are rarely specific to a given industry. The next chapter provides an in-depth description of the phenomenon of divergence as observed in practice.

5. Divergence

Understanding divergence, or the tendency for commonality to decline over the product family lifecycle, is critically important to understanding the benefits and penalties of commonality. This chapter provides a detailed description of divergence; a discussion of the case study evidence and findings as they relate to divergence; and an example of the potentially negative effects of avoiding divergence at all costs.

5.1. Description

Based on the case study findings, a platform-based product family development effort begins with a planning phase that represents a period of convergence[34], or the establishment of commonality plans that lead to an increase of commonality in comparison to the prior product family. The product family planning phase assesses market needs, corporate goals, available technologies, etc., in order to establish a high level plan for the product family, the individual product variants, and the underlying platform. The product family plan likely represents an optimistic estimate of the achievable level of commonality. (Refer to Figure 41, Point "A.") This optimism appears to be a combination of the optimism created by the initial decision to pursue platform-based development (e.g., employees echoing executive enthusiasm) combined with the need for program managers and their teams to establish aggressive program goals. Additionally, the team establishes the initial vision for commonality based on limited information with respect to market needs, internal requirements, and technology availability.

The interviews and limited case data indicate that commonality declines as the product family lifecycle progresses. The potential exists for new development efforts that increase commonality between products (Figure 41, Point "B"), although the case studies suggest that increases in commonality, beyond those associated with the initial platform planning effort, are extremely rare. The only significant examples of convergence post product family planning were associated with development of major new features (e.g., a new software control system in the semiconductor manufacturing equipment case). The military aircraft program data also seems to indicate an anomaly at the tail end of the data set. The data for the airframe indicates a significant reduction, followed by a later increase from the low point. (Refer to Chapter 4.) As was mentioned previously, none of the interviews associated with the military aircraft case indicated that a true increase in commonality had occurred, especially to the degree indicated by the data. The interview results combined with the explanation that the rise was due to a combination of changes in the way metrics are computed and to true increases in commonality make the increase somewhat suspect. Additional research would be required to validate these comments.

[34] "Convergence" is most accurate in the context of replacement of an existing group of products with a platform-based product family. The commonality strategy within the product family plan is typically anticipated to increase commonality. In the case of a truly new family of products, convergence is a less fitting term.

The term “divergence,” or the tendency for commonality to decline over the lifecycle of a complex product family (as illustrated in Figure 41), is utilized in this dissertation to describe both beneficial and non-beneficial losses of commonality. The phenomenon of divergence simply describes a trend that should be considered and accounted for in the evaluation, implementation, and lifecycle management of commonality.

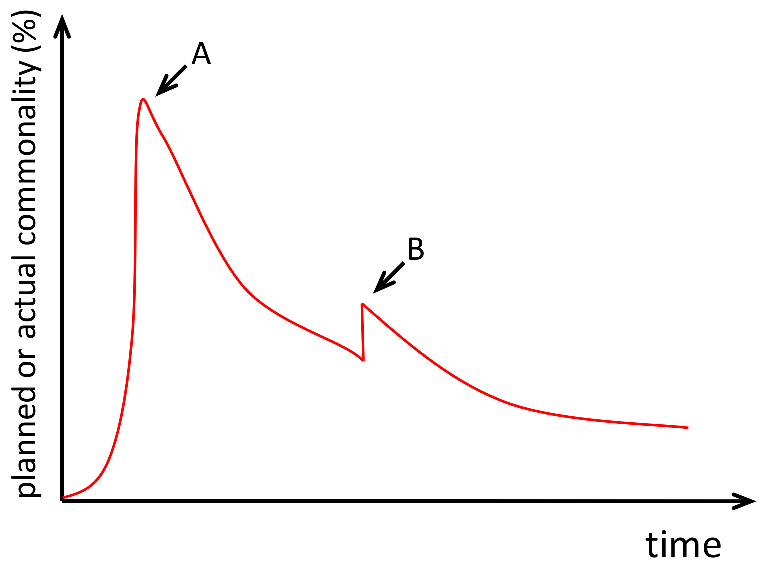

Figure 41: The notional evolution of commonality over time. Point A represents the output of the product family planning effort, an optimistic plan that was produced based on limited knowledge and in light of significant uncertainty. As time progresses, divergence occurs, and the “planned” levels of commonality decline as designs are created and implemented; i.e., as the plan becomes reality. Concerted efforts may be employed to reestablish commonality within the product family lifecycle (Point “B”), although the case studies suggest these efforts are rare and typically occur outside of individual product development programs.

Beneficial divergence should be recognized and encouraged while non-beneficial divergence should be avoided. Beneficial divergence occurs when profitability is increased relative to the alternative of maintaining commonality. For example, teams may need to address requirement changes; incorporate learning; integrate new technologies as they become available; and address component obsolescence issues. These changes modify the real or perceived technical feasibility of commonality and the economic incentives for maintaining commonality. In these cases, the reduction of commonality is completely rational and to be encouraged, as a net benefit is produced for the product family. In addition to the beneficial reduction of commonality, commonality may also be lost for non-beneficial reasons. Non-beneficial divergence results from a lack of product family perspective when making and implementing decisions that impact commonality. For example, a decision making perspective that independently considers a single product may produce benefits for this product, yet net losses at the product family level. Ultimately, rationally made changes are expected to increase profits; i.e., to be beneficial.

Rationality depends in part on the perspective with which a decision is made and product family decisions that potentially impact commonality are no exception. When a change impacts a common element, the change contains an explicit or implicit decision about maintaining or eliminating commonality in light of the full spectrum of benefits and penalties (e.g., other factors that influence profit) that are affected by this decision. Decisions about commonality are implicit when they are made from the perspective of an individual product. The outcomes of decisions made from this perspective (Figure 42, left) may or may not produce a net benefit from the perspective of the product family, the perspective that has the most direct connection to overall corporate profitability.

In the individual product mode of decision making, a rational decision maker selects decisions that are beneficial to his or her product (row indicated by red arrow). The decision maker examines the decision from the perspective of his or her product, without consideration of the broader implications; i.e., the impact to, or benefit from, other products. These decisions may produce a net benefit or penalty at the product family level, but the outcome is left to serendipity. Missed opportunities for increasing overall corporate profitability also exist in this mode of decision making. A rational decision maker who acts from the individual product perspective will never intentionally make a decision that impacts his or her product in a non-beneficial manner. The result is the potential for a missed opportunity; i.e. to take a loss at the product level in order to gain at the product family level. An example of this outcome is the observed lack of willingness of lead program managers to invest development funds in pursuit of Intended Common development: these investments produce penalties from the individual product perspective.

When a product family decision making perspective is utilized (Figure 42, right), improved decisions are made since decisions are approached from the perspective of corporate profitability rather than individual product profitability. In this case, the decision maker understands and acts from a multi-product perspective. A decision may be made which produces a negative outcome from the perspective of an individual product (e.g., increased development costs in comparison to the independent alternative), but produces a benefit at the product family level (e.g., reduced total development costs for the product family, or more importantly, reduced total lifecycle costs for the product family). Serendipity is replaced by improved perspective and explicit consideration of decisions that may or may not produce benefits for the company as a whole. In this case, beneficial decisions are made from the perspective of the product family (column indicated by red arrow). It is important to note that decisions made from this perspective *may* be the same as those made from the individual product perspective. The broader perspective includes the more narrow (independent product) perspective, ensuring decisions are as beneficial or more beneficial when made from the product family perspective.

The above description of decision making perspectives ties directly to divergence. The independent decision making perspective contributes to non-beneficial divergence by allowing non-beneficial changes to be made from the product family perspective. These changes were made in a rational manner from the perspective of an individual product but had negative outcomes at the product family level. Product family profitability declines as a result.

		Product Family Outcome	
		Beneficial	Non-Beneficial
Individual Product Perspective	Beneficial	Accepted (net gain)	Accepted (net loss)
	Non-Beneficial	Avoided (missed opportunity)	Avoided (loss averted)

		Product Family Perspective	
		Beneficial	Non-Beneficial
Individual Product Outcome	Beneficial	Accepted (net gain)	Avoided (loss averted)
	Non-Beneficial	Accepted (net gain)	Avoided (loss averted)

Figure 42: An individual product decision making perspective (left) may produce non-beneficial results at the product family level, even though these decisions benefit the individual product. The outcome: increases in non-beneficial divergence. A product family perspective to decision making (right) ensures that decisions are made from the proper perspective. Green entries represent desirable outcomes. Red entries represent undesirable outcomes.

5.1.1. Changes: The Potential Sources of Divergence[35]

Changes represent the potential sources of divergence. They are best understood by first examining change in the context of an independent design, then extending this discussion to the product family case. After discussing the general concepts, four classes of change sources are discussed: changing requirements; learning in development, production, and operations; availability of new technologies; and component obsolescence.

In an independent development approach, a single product is developed for a specific market segment, typically utilizing a Product Development Process that focuses on the development of a single product. Examples include the development processes discussed in Ulrich & Eppinger (2000) and Pahl & Beitz (1996) and the simplified product lifecycle view presented in Chapter 2. The simplified figure of Chapter 2 is presented here with additional detail in the development phase (Figure 43). The front end of the development process is characterized by attempts to understand the high level requirements or goals for the system while simultaneously exploring high-level concepts and their capabilities. The set of available concepts is slowly reduced as rankings are established and infeasible solutions are eliminated due to an improved understanding of the requirements. Eventually one concept (architecture) is selected and moved through the remainder of the development process. The product is then produced, operated, and eventually retired.

[35] Portions of this section are adapted from Boas & Crawley (2007).

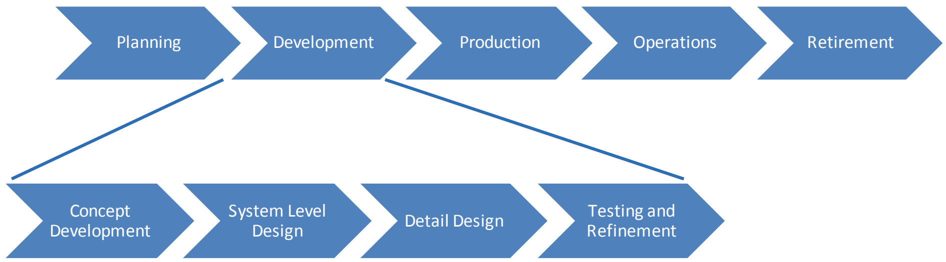

Figure 43: Product lifecycle view with additional development process detail.

In an ideal world, requirements would be established and fixed; concepts would be generated, analyzed, and selected based on these requirements; and design, test, production, and operations would progress in an error-free fashion. The reality is different and is well-recognized: the product lifecycle resides within a dynamic and often highly ambiguous environment and product development efforts are imperfect. Throughout the course of a product's lifecycle, requirements change; learning occurs; new technologies become available; and component obsolescence issues arise; all of which drive changes in development, production, and operations.[36] The net result of changes in the context of an independent design is the modification of the design, production, or operations systems with respect to those that were initially envisioned or initially implemented.

As the design matures, it morphs or drifts in a somewhat fluid manner. Drift impacts the overall cost, schedule, and risk associated with the development effort and, with the exception of scope reduction, changes during development can be viewed as increasing total development costs. Production and operations costs may be either positively or negatively impacted by change, depending on the nature of the change. Revenue also may either increase or decrease. The cost of making a change increases significantly with design maturity. Figure 44 illustrates a widely accepted anecdote regarding the relationship between design maturity (labeled as "time" in the figure) and the cost of change. This relationship is important for understanding the economic drivers of beneficial divergence as discussed later in this chapter.

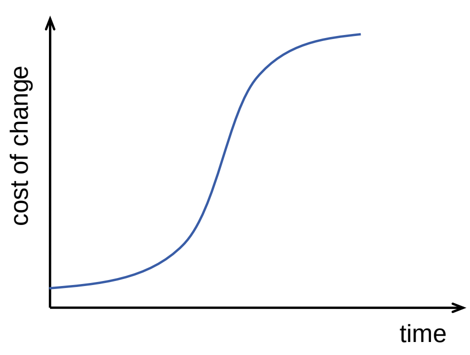

Figure 44: The increasing cost of a change with increasing time (design maturity) is a widely accepted trend.

[36] Eckert, Clarkson, and Zanker (2004) provide an excellent investigation into the sources of change. They classify changes into those that originate with design problems ("emergent") and those that are "initiated." Examples of the latter include new customer requirements and internally driven changes. Their classification is more complex than the one presented here, but their subcategories can be mapped onto this scheme.

Designs may experience significant degrees of change depending on the rates of change in requirements, technology, learning, etc. The maturation of immature technologies and rapidly changing requirements both tend to elevate change rates. Figure 45 illustrates one example of design changes in a single, evolving product, as calculated using the Commonality Analysis Tool developed as part of this research effort. The example represents several years of product data for one of the products in the printing press case. The history described by the data trend represents a nearly continuous set of changes that consists of continuous product improvements and the introduction of two "official" replacement models (at Periods 12 and 15). Only one model was produced at any given time. The red column at the left represents the original design as it existed at Period 1. At each period, the size of the red column indicates the remainder of the original design: the decreasing size of the red column indicates the elimination of originally developed components. As time progressed and changes occurred, the original components were replaced by new development (column segments above the original red column) and by reuse from other product models (column segments below the original red column). As indicated in the figure, changes have resulted in a significant amount of revision to the originally developed components, with the unchanged components being illustrated by the red column at the right side of the figure.

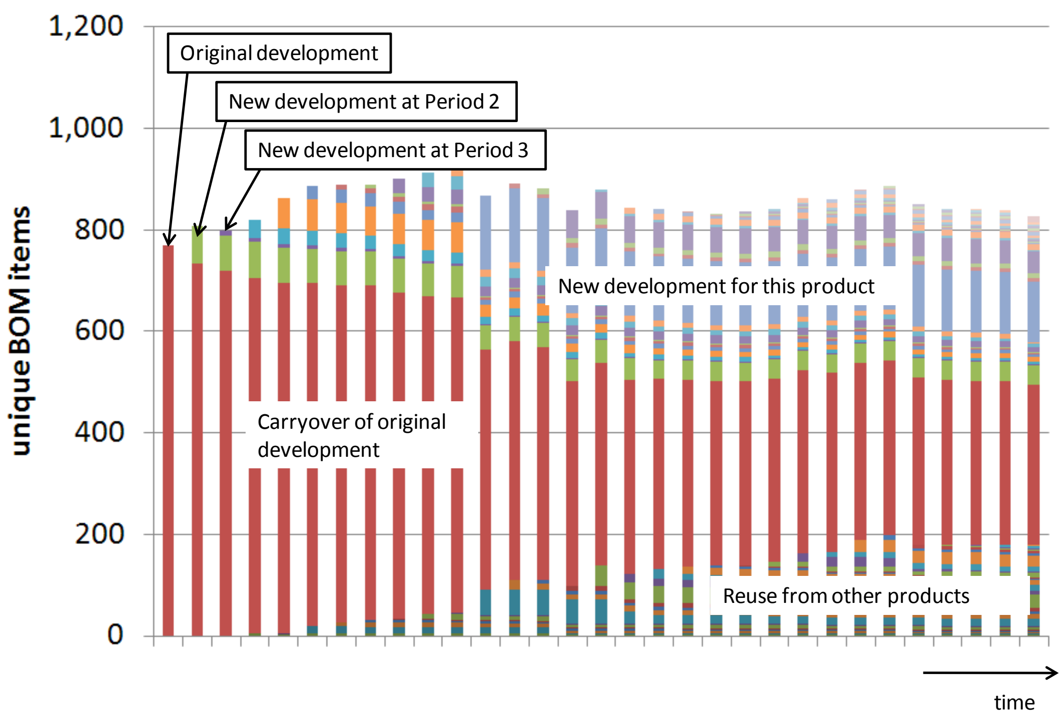

Figure 45: Reuse history for one of the printing press products (typical). Original components (red columns) are replaced by new development (column segments above the red columns) and through reuse of existing components from other products (column segments below the original red columns). (Parts costing less than $5 were removed. Chart represents several years worth of data. Time values intentionally removed.)

In the context of a product family, the same four change sources (requirements change; learning; new technology availability; and component obsolescence) found in individual product development efforts exist but may produce different outcomes. Figure 46 illustrates a high level classification of change in a two product context and the end impact of a given change classification on commonality.[37] The first decision branch concerns whether or not a potential change impacts an existing common element. A change that does not impact an existing common element may be implemented on either one or both products. In the case of implementation on both products, commonality is increased. Based on the case studies, increases in commonality, outside of initial establishment of the commonality strategy, seem to be extremely rare and only occur with concerted efforts such as those associated with the development of a new common feature that entails significant coordination across product family members. The second end classification in Figure 46 represents a previously unique element change that does not apply to both variants and therefore, has no impact on commonality. This class of change is similar to all changes associated with independent development efforts. The third class of change represents a change to a common element that is implemented on both products. As in the case of a change to a unique element, a change to a common element that is implemented on both products has no impact on commonality. Unlike the change to the unique element, the change to a common element modifies the platform core and corresponds to the dynamic nature of product platforms as described by Meyer & Lehnerd (1997), for example. Changes in this category represent true platform renewal efforts and do not result in a gain or loss of commonality between products. The last end classification, divergence, represents a change to a common element that is implemented on one, rather than both, products. Commonality decreases as a result. The case studies suggest that many of the changes to common elements result in divergence and that divergence occurs for economic, technical, and managerial reasons. Figure 46 highlights the fact that changes to common components only represent potential sources of divergence, rather than an immediate cause of divergence.

Divergence may be either permanent or transient. Permanent divergence results when a change is never implemented across both product family members. Transient divergence occurs when a time lag exists between implementation of a change in all previously common variants. Transient divergence may result due to factors such as the need to utilize existing inventory and/or on-order materials; the need to qualify changes for a subset of customers; and due to infrequent builds of a given system type. Transient divergence is important because it may result in the partial suspension of the benefits of commonality. For example, transient divergence results in a loss of manufacturing rate associated with a common part until the change has been implemented across all previously common variants.

In addition to classifying design changes based on their impact on commonality, the changes can also be classified based on their source type. Each source category is first discussed in the context of independent design, followed by extension to the product family case.

[37] The concept extends to more than two products, however, the explanation becomes more complex. For example, in the case of a three product family, the outcome of a change to a part that is common to all three products may be fully retained commonality, commonality between any two of the three products (three cases), and common to none of products (unique).

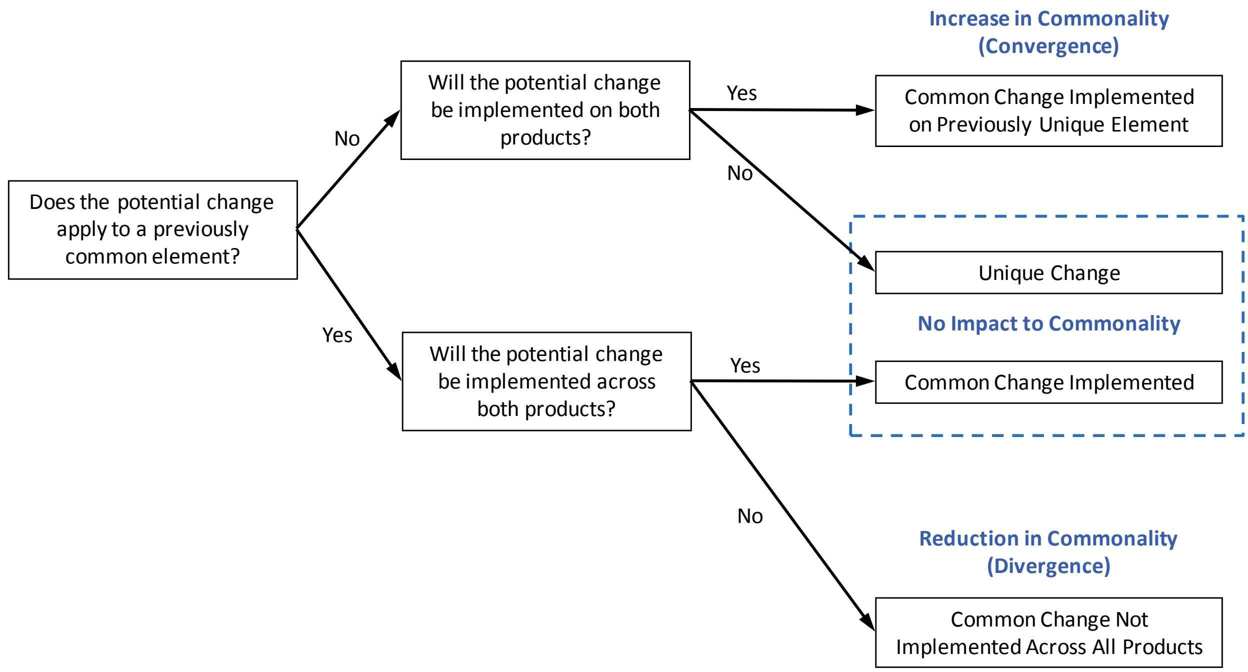

Figure 46: Change classification for a two product family. Changes may lead to an increase in commonality (almost nonexistent based on the case studies), no impact to commonality, or to a reduction in commonality. Divergence results if a change to a common element is not implemented across both products.

Changing Requirements

Requirement changes occur throughout the lifecycle of a given product, having the potential to drive changes to the system design, manufacturing process, and operations. These changes can be generated internally by the system integrator (e.g., a cost reduction program aimed at increasing gross margin); externally by the customer (e.g., a customer requires increased capability or a new feature)[38]; or externally by the competition (e.g., a competitor releases a new feature that must be matched in order to retain market share). Changes in standards and regulations (e.g., government safety regulations) may also serve as drivers for requirement changes.

Addressing requirement changes typically requires a development investment to be made (decreased development scope excepted) and may affect production (recurring) costs. The need for additional investments is most obvious when changing requirements dictate the need to repeat previously completed tasks. In terms of production costs, the effect may be either positive or negative. For example, a cost reduction program requires a development investment which is offset by recurring cost savings. As an alternative example, an increase in product performance requires a development investment and is likely to lead to increased recurring costs. In this case, a net economic benefit is expected as a result of revenue increases or a controlled reduction in benefit may be expected in light of competition.

[38] See Martin & Ishii (2002) for additional examples of externally driven requirements changes.

While requirement changes produce “drift” or a shift in an independent design, they may create divergence in the case of a common element used within a product family. The reasoning is as follows: a requirements change triggers, or should trigger, an evaluation of alternative strategies for meeting the new requirement. If all products are not subject to the same requirement change, their incentives for acceptance of the change are limited to any potential benefits of retained commonality. This decision should be examined from the perspective of the overall product family and the individual product family members. While the change may be necessary to gain or maintain the market share of an individual product, the change may not be needed, or may even be undesirable, from the standpoint of another individual product. For example, if the second product is in production and is not subject to the modified requirement, the investment required to implement the change may outweigh the benefit of doing so. In this case, requirements-driven divergence should result and is desirable.

The case studies consistently highlighted the challenges associated with changing requirements. For example, the automotive company faced significant variable cost requirement changes between development of the lead and follow-on variants. These requirement changes drove additional development work associated with the follow-on variant that was not utilized by the lead. The lead variant was in production and the variable cost benefits of the improvement would not have outweighed the high cost of making a late change.

Learning in Development, Production, and Operations

Learning occurs throughout the system lifecycle creating an incentive to modify designs, production methods, and operations. Designs progress from high-level, preliminary studies toward increasing levels of definition. As knowledge about the product designs increases, initial assumptions and design decisions may be overturned, driving the need for design modification. For example, design and requirements incompatibilities arise and must be rectified.[39] Production identifies unanticipated issues such as design errors and also opportunities for improvement in areas such as materials cost reduction, assembly time reduction, and quality improvement, to name a few. Operations (including maintenance) also generates valuable feedback about unanticipated issues or opportunities for improvement such as the need for initially unanticipated features, manufacturing labor reduction opportunities, and simplified maintenance. The new knowledge gained from these activities creates a need for design modifications, along with their associated benefits and penalties. In the case of independent design, these changes represent drift.

In the case of a product family, learning may lead to rational reasons for the elimination of commonality in certain components and processes. Commonality that initially appeared to be beneficial given a high level view and limited information slowly degrades for very good reasons. A better understanding of the market needs and product designs required to support these market needs results in divergence. Also, initial optimism about commonality levels is eroded with time. As an example, the military aircraft program has eliminated about 50% of its originally planned airframe commonality in order to meet required performance specifications. The core issue was not requirements changes but the understanding that comes with significant

[39] Refer to Lenfle, Jouini, and Derrousseaux (2007) for additional discussion.

investment (of time and money) in design: through learning in design, the team realized that use of certain common components had an unacceptable weight impact. Meeting performance requirements was mandatory, whereas commonality was nothing more than a potential tool for cost control. Clearly, the elimination of commonality was beneficial in this case.

Availability of New Technologies
Technological progress always presents development teams with the decision of whether to insert new technologies into their designs or utilize existing technologies. New technology insertion requires investment. Returns are expected from the standpoint of revenue, cost, or possibly risk. The importance of the new technology insertion question increases with increasing differences between the relative lifecycles of the product and its subsystems. For example, computer processors and software both may have very short lifecycles, yet may be utilized in aircraft that may have lifecycles of several decades.[40] Improvements in processor technologies and software capability may offer compelling benefits that drive design modifications.

In the context of a product family, new technology development and insertion would need to occur across all product variants in order to maintain commonality but doing so may not be economically justified. If the benefits of a new technology are unattractive to a given variant, the investment may not be made for that particular variant and divergence will result.

Component Obsolescence
While closely related to "Availability of New Technologies," component obsolescence is listed separately because the driver for change is different. The obsolescence of a given subsystem (take the computer processor, for example) *forces* a design change due to the pending unavailability of a part or subsystem. "Availability of New Technologies" represents an opportunity. "Obsolescence" represents forced action assuming the product is retained.

5.1.2. Enablers of Divergence

The change classifications described above represent nothing more than potential sources of change that may lead to divergence. Without change, common components will remain common. Also, as illustrated in Figure 46, a change to a common component that is implemented across all products that share the component represents the dynamic nature of the underlying platform and does not in itself lead to a loss of commonality. What does lead to a loss of commonality is the implementation of a change on a subset of the products that initially shared the common component.

Two main enablers of divergence exist: economic incentives and lack of coordination at the product family level. Both are described briefly below.

Economic incentives to specialize previously common designs mean that the elimination of a common component is desirable and should be encouraged; i.e., that the revenue or cost

[40] Refer to Charles Fine's book on the concept of "clockspeed" for more information on lifecycle mismatches (Fine, 1998).

benefits of uniqueness outweigh the benefits of commonality. The military aircraft case, specifically, the weight reduction effort associated with the STOVL variant, provided the best example among the seven case studies of divergence that was allowed to occur based on economic evaluation criteria. In this case, reduced weight parts were required to maintain the performance of the STOVL variant. Had the changes not been made, the STOVL variant would not have been a viable aircraft and the economics of the product family would have been severely impacted. In many cases, the economic benefits of maintaining commonality between the STOVL variant and the other two variants did not outweigh the cost of implementing changes on the other variants, both in terms of development investments and increased component manufacturing costs that often came with weight reduction. In this case, technically feasible changes did not provide an economic benefit and were rejected for this reason. As an additional example, the automotive case required the elimination of a common brake design in order to meet the truck (follow-on variant) requirements of maintaining revenue and controlling costs.

The case studies identified the cost of change implementation as a specific economic incentive for divergence in the case of sequentially developed product families. The costs of change implementation vary significantly in the sequential development context of complex products: implementation of a given change in previously developed variants may cost orders of magnitude more than implementation during a current product development program. An idealistic view of commonality (calculating benefits based on a parallel development view, given the sequential nature of complex product family development) would suggest the hypothesis that a significant degree of improvements made to common elements would be folded into all existing variants in order to maintain commonality. The case studies consistently struck down the above hypothesis: improvements associated with later variants are rarely folded into existing product models, barring resolution of a major issue such as a safety concern. In some cases, development teams explicitly avoid implementation of improvements into previously developed product variants, a concept termed "backward propagation" of change in this dissertation. Backward propagation of a change has a high associated cost in relation to implementing the change in a new development program, due to the costs of modifying an in-production design (Figure 47). The high costs of implementing a change in an established product design are likely either to outweigh the benefit of implementing the change or to provide an unattractive return on investment. This phenomenon is common in industrial practice, but not does appear to be recognized as an economic driver of divergence during platform planning and evaluation and within the academic literature on product platforms. The phenomenon represents a core difference between the parallel development assumptions of the literature and the sequential nature of complex product family development.

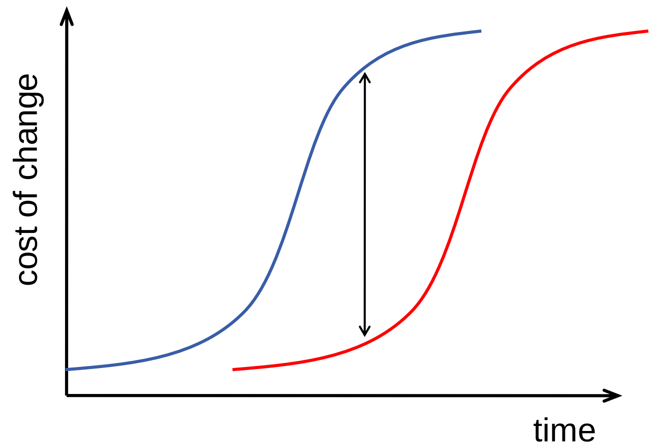

Figure 47: The cost of a change increases with time (design maturity). In the context of offset lifecycles, programs may realize significantly different costs associated with implementing a given change. The double headed arrow indicates the notional cost of making a change to a lead variant design (blue line) versus a follow-on variant design (red line), given the case of a two product family.

The second main enabler of divergence, lack of coordination at the product family level, results in a lack of proper decision making scope and the potential for non-beneficial divergence as was discussed earlier in this chapter and as was illustrated in Figure 42. Lack of coordination means that changes to common assets are not considered and managed from a multi-product viewpoint. For example, decision making power in the organization may be focused on independent program decisions. The limited decision making scope cannot value the potential benefits of commonality which are inherently multi-product. While an uncoordinated change may produce a net benefit to the product family, any gain is produced through serendipity.

Also associated with "lack of coordination" is a lack of ability to coordinate. For example, making the connection between revenue and development decisions is extremely difficult, especially at lower levels of the design hierarchy, and this difficulty is compounded by the need to consider multiple products. One of the strongest case study connections between design decisions and product revenues was identified in the automotive case. The automotive company had years of history with similar products that gave the company high confidence in its ability to predict the revenue impacts of very detailed design decisions. Additionally, the commercial and military aircraft case companies made a strong connection between weight and aircraft operating costs; costs that were critical to customer purchase decisions. Beyond the existence of clear relationships between design decisions and high level customer needs lay a nearly countless number of decisions that have a much less precise revenue connection. Without a clear understanding of the lack of revenue received from non-differentiating features, engineering design "optimization"[41] of the individual product variants may be pursued to the detriment of profitability.

[41] Here "optimization" refers to design team attempts to create products that match the needs of a given market segment as closely as possible. "Optimization" is not used in the formal mathematical sense.

Figure 48 provides a summary of the potential sources of divergence (sources of change) and the enablers of divergence. Changes represent well-intentioned changes to one or more products. The enablers determine the outcomes of these changes with respect to corporate profitability. Lack of coordination may lead to either non-beneficial divergence or beneficial divergence through serendipity. Economic incentives for divergence imply consideration of decisions at the product family level and imply the existence of a net profit benefit to the corporation.

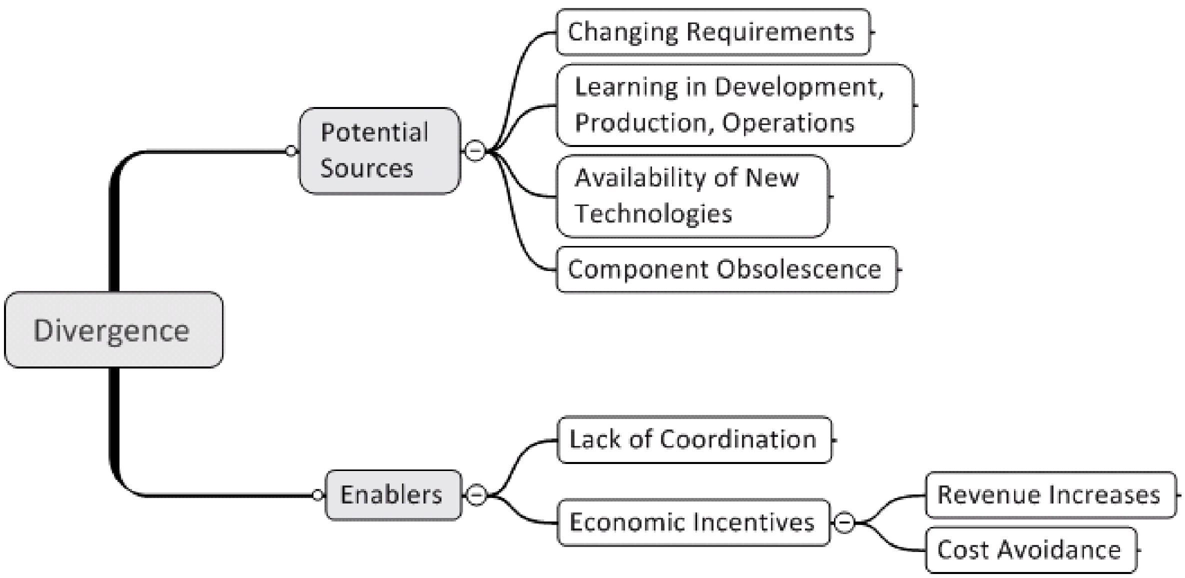

Figure 48: Summary of potential sources of divergence and their enablers. Lack of coordination may result in non-beneficial divergence. Economic incentives for eliminating commonality imply the existence of a net benefit.

5.1.3. Modeling Divergence

Several example patterns of divergence are presented here to illustrate potential alternatives (Figure 49). This research provides enough qualitative and quantitative data to illustrate the existence of the overall phenomenon, but additional field research would be required to accurately characterize the trends to the degree that they could be fit to patterns, mathematical descriptions, etc., with higher degrees of certainty. An asymptotically increasing trend is a reasonable first approximation for the degree of divergence (one minus the commonality percentage). Other trends include the potential for increasing commonality (negative divergence), constant commonality, linearly increasing divergence, and S-curve-like increases in the degree of divergence. Shorter term views of divergence are likely to produce less predictable responses as the curves ultimately consist of collections of many changes. Large change efforts such as a cost reduction program may produce more obvious step changes in commonality. The patterns of divergence are likely to vary widely in industrial practice, although further research is required to confirm or reject this hypothesis.

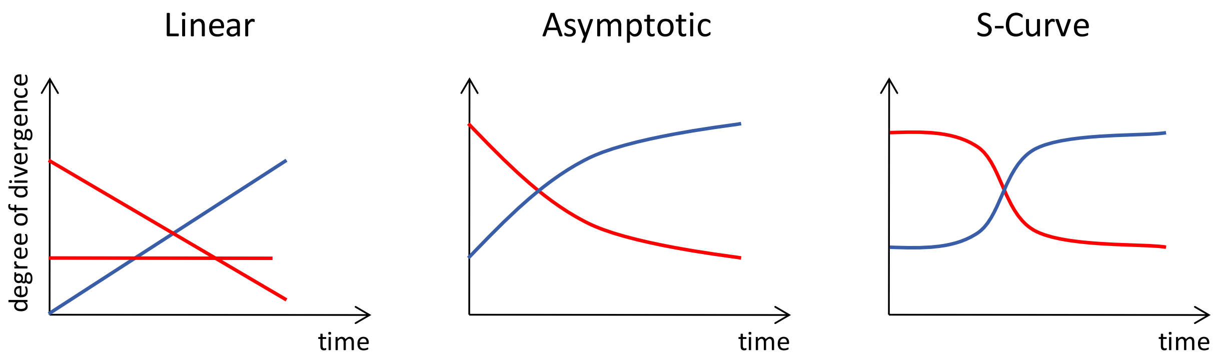

Figure 49: Examples of potential divergence trends include linear, asymptotic, and S-curve. Increasing trends (blue lines) are expected based on the field research. The red lines are unlikely "divergence" patterns (with the possible exception of the horizontal red line at left). An asymptotic increase in the degree of divergence (the degree of lost commonality) is assumed for modeling purposes (Chapter 6). The degree of divergence is subtracted from one to obtain the remaining degree of initial commonality.

For later modeling purposes (Chapter 6), divergence is assumed to be defined by the following asymptotically increasing function that is dependent on time, n, and a decline rate, β. The remaining commonality, $Reuse_{IC}$, is calculated by subtracting the divergence value from one. See Equations 5.1 and 5.2:

$$Div = 1 - \frac{1}{(1+\beta)^n} \tag{5.1}$$

$$Reuse_{IC} = \frac{1}{(1+\beta)^n} \tag{5.2}$$

Where β is a decline rate that determines the reuse of Intended Common elements at any given time. When β is equal to zero, no divergence occurs and all Intended Common elements are reused. When β is non-zero, reuse of Intended Common elements is less than 100% for all times greater than zero. The decreasing function presented here seems to be a reasonable trend based on the case studies. The actual function depends on a given company and the history of a given program.

5.2. Evidence of Divergence within the Case Studies

Prior to conducting the case studies, the phenomenon of divergence had been constructed as a hypothetical framework for explaining the evolution of commonality throughout the product family lifecycle. The original concept focused on the negative, or non-beneficial, aspects of divergence and as such, viewed divergence as a phenomenon that was to be avoided through careful planning and lifecycle management. The initial hypothesis was intended to reduce the seemingly overly optimistic views that result from applying the product platform concepts and tools found in the literature to the complex product family context.

Based on the seven case studies, a refined view of divergence has emerged. Most important was the change from a focus on non-beneficial divergence to a more neutral view. Divergence was originally conceptualized as a trend that was to be prevented, but the cases made clear the fact that divergence in itself is neither beneficial nor non-beneficial. For example, a reduction in commonality may produce revenue gains that outweigh the loss of any commonality-driven cost benefits. The refined view, as described previously in this chapter, recognizes the need to allow beneficial divergence to occur while minimizing divergence that results in net losses to product family profitability. The field research also helped to refine the potential causes of divergence and reinforced the dynamic nature of common elements; i.e., the fact that common elements change to meet future needs, address opportunities to leverage new technologies, etc.

An attempt was made to examine divergence from both qualitative (interviews) and quantitative perspectives. The interviews provided consistent feedback with respect to the existence of divergence in each of the product family histories: divergence is prevalent and occurs due to both rational considerations (assumed here to tie to economics) and through a lack of coordination. Given the sequential nature of complex product development, the economic incentive for maintaining commonality is reduced by the high cost of implementing changes into existing products. Lack of coordination is also accentuated by the sequential nature of complex product development. Low degrees of coordination were often observed with respect to common element decisions: decisions were often made from an individual product perspective, rather than a product family perspective. The case study observations of low degrees of coordination between product family members led to the hypothesis that levels of non-beneficial divergence are likely significant and their management represents a significant opportunity for improvement in product development practice.

While one of the field research goals was to quantify divergence within each of the product families, this outcome was only partially achieved. Data access and data quality issues both limited my ability to estimate commonality levels and their evolution. Additionally, the inability of the Commonality Analysis Tool to estimate commonality at levels lower than individual parts prevented the analysis of part level similarity, which was often cited by interviewees as a key beneficial outcome of common development. For example, two aerospace structural parts may share common attributes such as material type and nearly identical geometries with the exception of changes in wall thicknesses. These components are manufactured on the same production lines and are assembled using the same tooling. In this case, substantial benefits from similarity at the part level are realized in practice, yet go undetected by an automated analysis of commonality. As was discussed in Chapter 2, similarity is subjective and not easily measured in an automated manner.[42] Lastly, the two cases that involved Bill of Materials analysis were limited by the fact that early design definitions could not be analyzed for each of the product family members. The Commonality Analysis Tool analyzes production versions or close-to-production versions that have formalized Bills of Materials (i.e., part numbers have been assigned). The rate of divergence is likely related to the degree of change in the design

[42] The reader is reminded that assembly level similarity can be easily analyzed through an automated Bill of Material analysis, such as the analysis performed by the Commonality Analysis Tool. Similar assemblies consist of common and unique parts, both of which can be detected. The analysis is ultimately limited at the level of similar parts, which are classified as unique by a part number-based Bill of Material analysis.

which, based on the case study interviews, is hypothesized to be highest in the early phases of a development program.

The lack of commonality data represents a case study finding in itself. Prior to the case study research, commonality metrics were expected to be tracked by all seven case companies. Only one of the case study companies, the military aircraft company, has tracked commonality from the development process forward. This outcome was surprising given that all seven companies pursue some degree of a platform approach to product development. Tracking commonality represents a *potential* future step for companies that want to better understand what happens to their platform plans throughout the product family lifecycle. Understanding the historical evolution of commonality in past programs may aid companies in creating more realistic evaluations of the benefits of platform-based product family strategies in comparison to the independent product alternative. Understanding the historical outcome of commonality through metrics is not the same as using commonality metrics to drive program execution. The latter approach may create problems as high levels of commonality are not an end goal.

Several of the case studies did produce data in the form of tracked commonality metrics, program financial records, or raw product data that was then analyzed using the Commonality Analysis Tool. The information, both qualitative and quantitative, obtained for five of the seven cases is discussed below.

Automotive (Case A)

The automotive case (Case A) illustrated a common trend cited in several of the cases (e.g., automotive, military aircraft, commercial aircraft): initial plans for common components shift toward similar components and common processes as time progresses. The interviews illustrated the realization of high degrees of component similarity (i.e., partial attribute commonality within individual parts) and limited degrees of exact commonality at the component level (ending up at a few percent). While a planning phase goal for the percentage of common parts was not identified during the case study, a review of early program planning documents suggested that commonality was anticipated to be much higher than a few percent. During the case study interviews, the most widely mentioned example of divergence was the decision to eliminate an Intended Common brake design due to the following vehicle's (truck's) reduced braking capability requirement and more stringent corporate cost and weight goals. In this case, the decision to move away from common brakes was supported by analysis and appears to have produced a net benefit for the company in terms of both revenue and cost. It is important to note that the selected brake alternative was a modification of the prior truck model year brake, meaning that a recurring cost benefit for the truck brakes was realized with minimal nonrecurring investment and risk. The development penalty associated with developing a modified design was substantially reduced in relation to creating a new design.

Commonality also reduced from initially anticipated levels due to the time offset between the SUV and truck models (approximately two years). As described in the case study summary, this offset created a resource imbalance between the two programs that led to an inability of the truck team to bring detailed design studies to negotiations with an SUV team that was able to produce detailed studies. Platform decisions had to be made with limited information about the truck requirements and an imbalance in decision making influence. The resulting decisions, sometimes knowingly and sometimes unknowingly, represented compromises on the truck design. These decisions later led to divergence because the required truck design compromises turned out to be unacceptable. In this case, technical and/or economic infeasibility were introduced into Intended Common designs that later had to be revised to meet the true needs of the follow-on truck program. Any additional expenses associated with development and production (e.g., manufacturing cost associated with excess capability that is not offset by shared economies of scale and learning) of the original, Intended Common designs represented waste in this case.

Military Aircraft (Case B)
As with the automotive case, the military aircraft case started with a high degree of emphasis being placed on creating common parts and processes. The roots of the program had focused on highly common aircraft designs, with a high degree of commonality being realized on the actual flight demonstrators (prototypes). As development of the post-demonstration phase variants proceeded, the emphasis shifted from common parts and processes toward similar parts and common processes: increases in design knowledge and requirements maturity made the tensions between commonality and performance more obvious and sometimes unacceptable. In some cases, such as the airframe design, commonality had to be undone in order to produce aircraft designs with acceptable performance: overly optimistic commonality plans had to be corrected. Multiple interviewees stated that the use of common processes and similar parts provided a good compromise in terms of achieving the significant manufacturing benefits of process commonality without unduly penalizing the technical performance of each variant. Additionally, the similar designs provided learning curve benefits in engineering development.

As was presented in the military aircraft case study report (Chapter 4), the evolution of commonality has been tracked by the program team for three classes of components: Mission Systems, Vehicle Systems, and the Airframe. Of the seven cases, this data provides the best quantitative insights into the early evolution of commonality in complex product families as the data was based on early configuration data, rather than production part numbers. The initial metrics were based on the weight totals of common, similar, and unique components; an outcome that was necessary due to a lack of design definition early in the program. As the aircraft transition into full-rate production, the commonality metrics will transition to part number and cost-based metrics.

Changes in commonality vary significantly over the three high-level component classifications (Mission Systems, Vehicle Systems, and Airframe). (Refer to Figure 50 for data for one of the variants, the CTOL aircraft. Refer to the case report in Chapter 4 for the full data set.) Commonality within Mission Systems has remained essentially constant with the exception being the requirement for a gun on one of the variants (CTOL). Vehicle Systems have seen a decrease of approximately 18%. The airframe has seen the most significant reduction in commonality at just over 50% of the original level. The team has linked the increased loss of commonality in the airframe to the tight coupling between performance requirements and structural design. The weight difference between designs that meet the superset of requirements for the three aircraft variants and those that are "optimized" to meet the needs of the individual variants are significant. These weight penalties were often unacceptable and led to beneficial divergence.

The commonality data in Figure 50 also illustrates an anomaly: unexpected rises in commonality levels are observed in later periods of the Vehicle Systems and Airframe trends. The rises were explained by the company as a combination of definitional changes and true increases in commonality due to the realization that certain components could be made common. The relative proportion of the rise due to the two categories is unknown, although the interviews for the case study did not indicate any increases in commonality as the development program progressed.

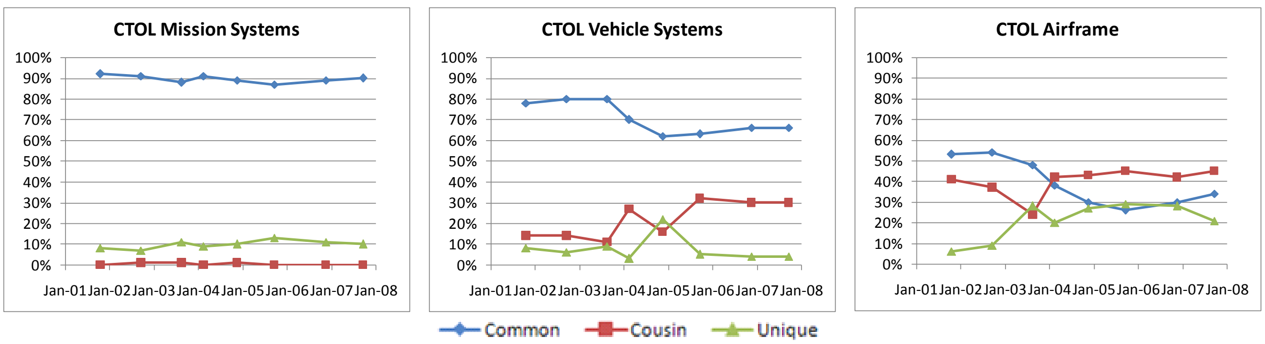

Figure 50: The evolution of commonality varied by subsystem type in the military aircraft program. Common part levels have stayed nearly constant for Mission Systems. Commonality has, for the most part, decreased with time for the Vehicle Systems and Airframe classifications, while unique and cousin part levels have risen. The company explained the reversal of this trend for the final two data points as being caused by definitional changes and the realization that some parts were similar. The relative proportions of the two categories could not be determined.

While changes occurred throughout the development history, a significant weight reduction event (STOVL Weight Attack, SWAT) drove a large portion of the divergence. During the SWAT effort, large amounts of weight were removed from the STOVL variant and these weight reductions led to the creation of similar and unique parts. The changes were required to create a STOVL variant with acceptable performance and their impact was often assessed from the perspective of the other two variants. In many cases, technically feasible improvements (i.e., improvements that maintained commonality) were rejected for economic reasons.

The military aircraft program appears to have done, and appears to be doing, an excellent job considering the impact of changes made to one aircraft on the entire aircraft family. The sequential nature of development and the desire to minimize design changes in previously developed variants both appear to have contributed to reducing commonality over time. In these cases, the team appears to have acted rationally: the backward propagation of changes made to common components would have produced a negative economic outcome from the product family perspective.

Printing Presses (Case E)

Company E heavily leverages its core printing technology across multiple products, as described in the case report summary in the Appendix. The investments in printing technology development eclipse individual product development efforts in the generation of products that was within the scope of the case study. Follow-on products have required investments of between 5% and 15% of the original, combined investment in the underlying printing technology and the lead variant. High degrees of reuse occur between products and this reuse is primarily linked to reuse of Intended Unique components as opposed to reuse of planned platform components.

From a qualitative standpoint, a high degree of divergence appears to have occurred between the products, especially during the development phase. For example, the original lead variant was intended to be a "speeded up" version of the prior generation of products with an executive mandate for minimal modification. As development progressed, the scope of change increased dramatically and in the end, one interviewee estimated that roughly 80% of the prior product was modified to create the lead variant. These changes were required in order to meet new requirements. As an additional example, consider development of early Product Line 2 products, which were intended to be based on the original printing engine technology and lead variant design. The initial vision was "simple": combine the original printing technology core with a substrate handling system from another product line. The reality was that many design modifications had to be made to accommodate the more stringent requirements of Product Line 2. For example, the substrate handling mechanism had to be modified for single printing core operations and to meet more stringent operational requirements. Also, the electrical cabinets were modified to remove unnecessary cost and footprint, given reduced electrical requirements. The Product Line 2 development program also required the addition of several new features that had not been developed for the other product lines. Other features were deleted; e.g., the second printing press core and paper inverter.

The Product Line 2 development progression described here represents a typical product development program. A baseline is identified. New features are added to the baseline to meet the new market requirements and unnecessary features are subtracted. The baseline is modified as required to accommodate feature addition and subtraction and to meet the new market requirements. The outcome: divergence results. In the case of Product Line 2, the resulting products were extremely successful in the marketplace.

Product Bill of Material (BOM) data was available for the printing press case. This production data represents a relatively stable portion of the product design in relation to the changes that a design undergoes throughout the development process. Even given this stability, the product history for two of the product lines demonstrates a reduction in commonality over time (Figure 51). The initial products for the product lines illustrated in Figure 51 were developed in a sequential manner, with a high level of carryover intended between the two product lines. Product PL3-1 was introduced during Period 1, followed by the introduction of Product PL2-1 at Period 5. As time has progressed, the product BOM's have experienced significant degrees of change. The figure illustrates a significant level of commonality based on part count (71% in Period 6) and also a reduction in this commonality level over time (26% absolute reduction from Period 6 to Period 26). The source of the common parts could not be determined from the automated analysis. In other words, the parts may have been arrived at through either reuse of Intended Common components or Intended Unique components. Regardless of their initial source, the trend was downwards with time; an observation supported by the interviews. In this case, the downward trend was clearly a combination of improvements that addressed internal learning associated with development, testing, and manufacturing; field learning; and the incorporation of new technologies and features. The reader is cautioned that reported results are based on unique BOM line items rather than on normalized cost, a necessary outcome due to the method with which cost is reported in Company E's BOM's.

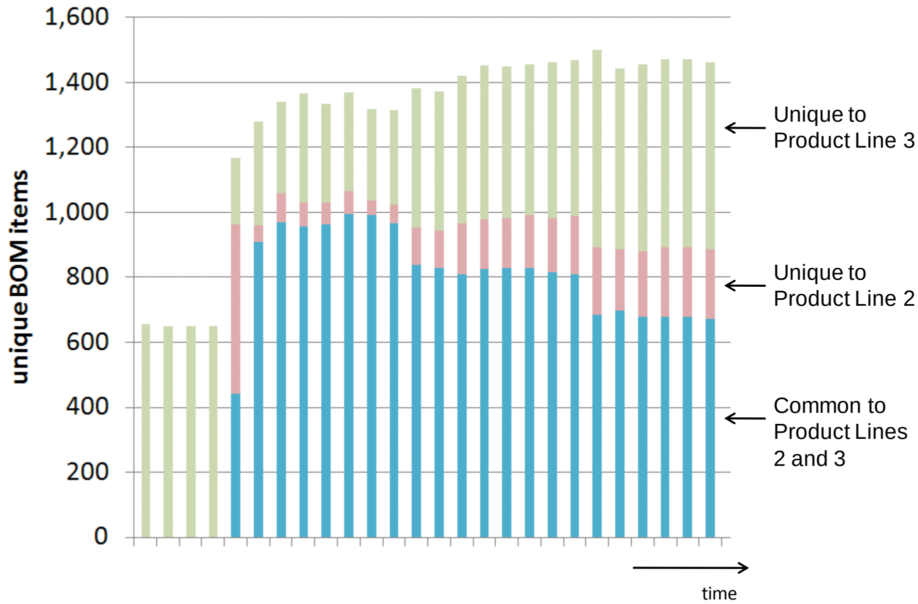

Figure 51: An analysis of Bill of Material data for two of the printing press company's product lines. The number of common components (labeled blue columns) has declined with time while the total number of unique parts (red and green columns) and total number of parts have both increased. The step reductions in commonality at times 13 and 21 align with product version changes in one of the product lines. (Parts costing less than $5 were removed from the scope of analysis. Time values were intentionally removed.)

Figure 52 illustrates the evolution of commonality (sharing) levels throughout the entire printing press product family history as studied. As time has progressed, the total number of parts has increased significantly due to the addition of new products and increasing product complexity. Between Period 11 and Period 30, the number of common elements (defined as being common to any two or more product lines) has decreased by about 14% while the total number of parts has increased by 84%: the relative reduction in commonality is much more significant than the absolute reduction. Figure 52 also illustrates the impact of major new model introductions, such as PL1-1 and NPL1-4. Introduction of new minor models did not have a significant impact on part count distributions, supporting interview comments regarding the incremental nature of follow-on products in a given product line.

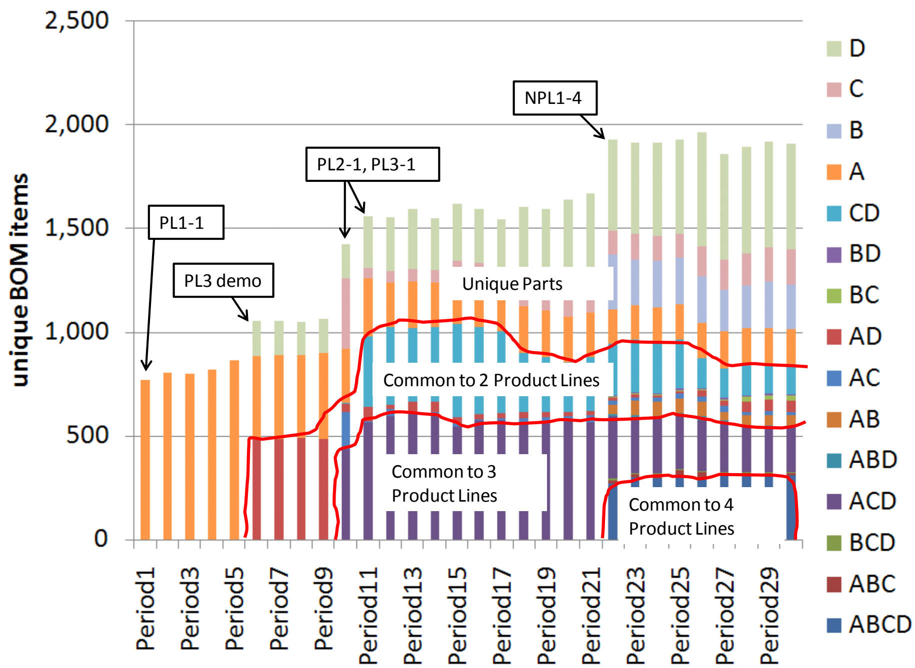

Figure 52: A part sharing analysis of Company E's printing press product lines. The chart illustrates unique parts and parts common to two, three, and all four product lines. Legend letters correspond to Product Line 1 ("A"), NPL1-4 ("B"), Product Line 2 ("C"), and Product Line 3 ("D"). The relative reduction in commonality is more significant than the absolute reduction. Red lines separating commonality classes are sketched and inexact. (Parts costing less than $5 were removed.)

Semiconductor Manufacturing Equipment (Case G)

The semiconductor manufacturing equipment company has approached product development in a mostly independent manner, with the most recent programs studied providing exceptions to this statement. The bulk of the products studied were created through modification of prior product baselines. Intended Common components are routinely modified in order to meet the requirements of each new product. The mainframe provided the best example of divergence between product models as time progressed. The initial mainframe was intended to be a common mainframe but the reality on the manufacturing floor is that major assembly differences start at the first assembly station where the potential exists to select from one of three types of frame structures; one of four process chambers; and one of two wafer handling chambers. Feeder lines also manage high degrees of complexity in areas such as wiring harnesses. Design, manufacturing process, and inventory complexity have all risen as commonality has declined. Costs associated with this complexity could not be determined during the course of the case study.

A critical exception to the trend of divergence in Company G's common components has been the creation of a common software system that is configured for each specific product. The high costs, lead times, and risks of developing a new software system are prohibitive from the standpoint of any one product, meaning that these prohibitive costs contribute to the preservation of commonality; i.e., an economic benefit of commonality exists and is easily recognized. The common software system is a widely recognized success within the company and was mentioned by multiple interviewees. Company data supports the existence of a substantial savings related to reuse of this software system in each new product.

Analysis of data from the semiconductor manufacturing equipment company provided some additional insights into changing commonality over time. Figure 53 compares the initial baseline, Product A, for one of the product lines to Products B and C based on normalized material costs. Products B and C are derivatives that were developed after Product A and somewhat in parallel with one another. The differences between variants A and B, A and C, and B and C indicate changes were required to enable innovation and differentiation within the product line. The common platform as realized in the actual products represents approximately 60% of the total Product C cost, a significant material cost fraction. Products A and B share materials valued at 7%, as normalized against the Product C total. Additionally, Products B and C share 17% of their materials costs with one another, as normalized against the Product C total. This Product B-C common block represents innovation beyond Product A that was leveraged across Products B and C, but not folded back into Product A. The unique portions of Products B and C represent required differentiation and possibly, missed opportunities for commonality. The split between the two categories could not be evaluated with the automated analysis tool.

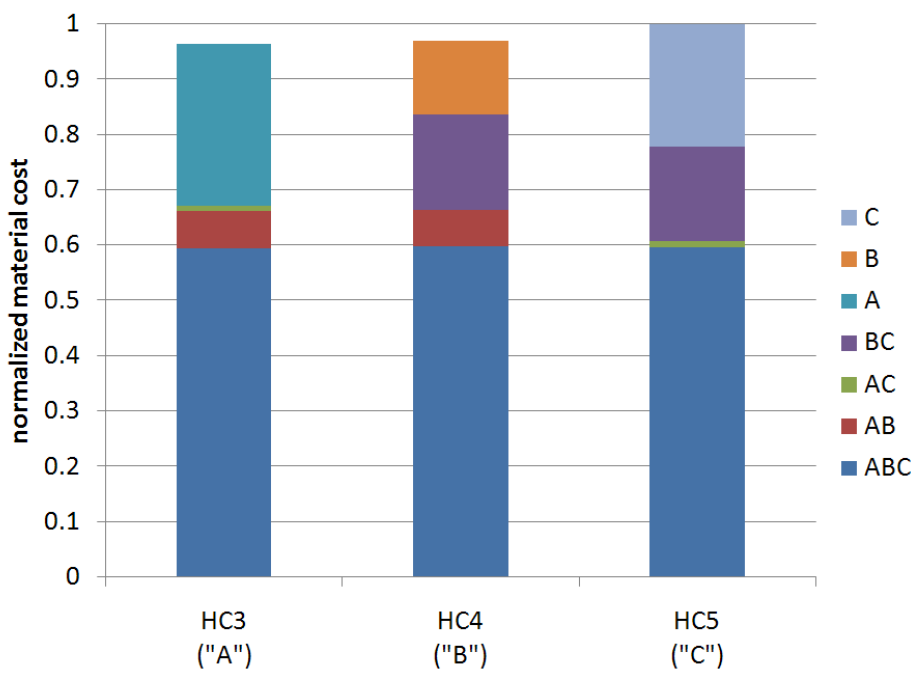

Figure 53: Company G data illustrating normalized material costs across one of Company G's product lines. Products B and C represent somewhat parallel development of two follow-on variants of Product A. Materials valued at 60% (normalized against the Product C total) are shared between all three products. Materials valued at 17% of the Product C total are shared between the newest products in the family, Products B and C. Also note that materials costing 7% of the Product C total were carried forward to Product B from the Product A baseline, but not utilized in Product C.

Communications Satellites (Case F)

The communications satellite manufacturer followed production of its initial few satellites with the creation of a formal vision for a scalable product family (and underlying platform or "bus"). Due to low production volumes, high degrees of market uncertainty, and resource limitations, Company F was unwilling/unable to fully create the underlying platform as a separate development effort. As a result, the company conducted Intended Common (platform) development as part of individual satellite development programs for specific customers. The Case F interviews clearly indicated that changes to the underlying Intended Common elements (the bus) were required for many new satellite programs, even though the original intent was to develop a set of common elements that would support a broad range of customer needs and, therefore, would not require later modification or replacement. Individual programs were charged with development of common elements and, as a result, these elements were skewed towards the needs of the current program at the expense of the less certain needs of future programs. Given resource limitations, market uncertainty, and limited production of any given design (one to three satellites), this was likely the best approach to development. Significant follow-on investments in the platform were incurred as a result of this approach (Figure 54); investments that went well beyond the initially anticipated level of investment as specified in the original product family plan. The alternative to making the follow-on investments would have been lost customer orders; clearly an unacceptable outcome.

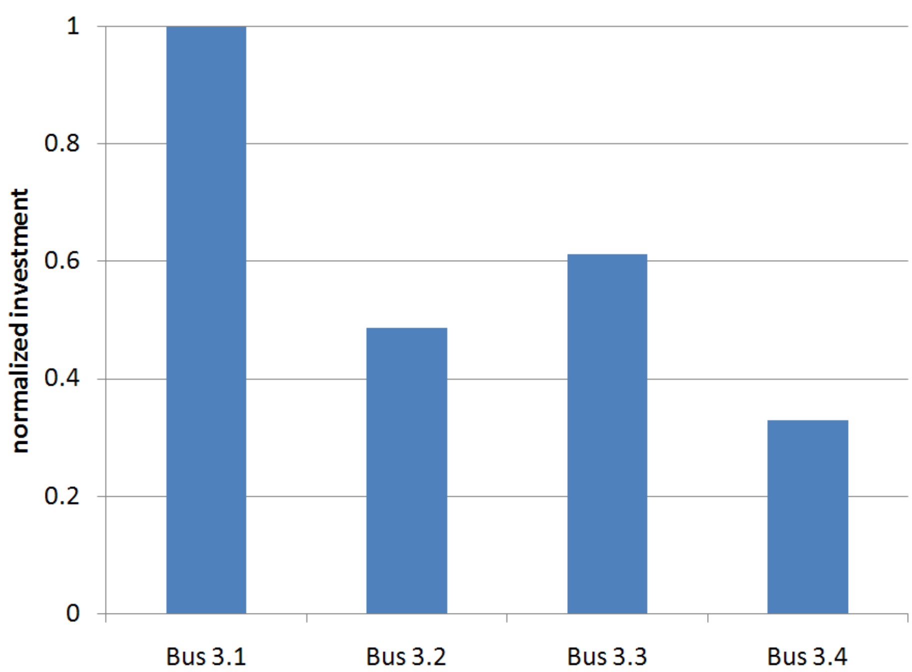

Figure 54: Normalized investment in each bus (platform) configuration. The high Bus 3.1 investment was likely inflated due to challenges faced by the manufacturer that were not directly related to commonality and platform development. The follow-on investments in Intended Common elements essentially represent the development costs of divergence for this specific case, although these costs were likely unavoidable given the high degree of market uncertainty and low satellite production rates.

5.3. A Caution Against Overly Strong Attempts to Avoid Divergence: The Tactical Fighter, Experimental (TFX)[43]

While this chapter's discussion of commonality has focused mainly on beneficial and non-beneficial losses of commonality, it is also important to consider the potential negative impacts of avoiding beneficial (or required) divergence. The Tactical Fighter, Experimental (TFX) military aircraft program of the 1960's provides an extreme example of failure to allow beneficial divergence to occur as required to produce successful aircraft variants. This program was created by then Secretary of Defense, Robert McNamara, who had elevated commonality to the "status" of a program goal.

Initially (February, 1961), the TFX program was intended to develop one aircraft that would fulfill the multiple mission needs of the United States Air Force, Navy, Marine Corps, and Army, although within 5 months, the program was focused on meeting the needs of the Air Force and Navy with one common aircraft (Art, 1968). McNamara expected that the selection of a single aircraft design for both services would produce a lifecycle cost savings of $1 billion (TFX Contract Investigations, 1964, p. 382) on a program that was projected to have total program costs of $7 billion at the time of the final concept evaluation (TFX Contract Investigations, 1970, p. 30), although this estimate was disputed.

The significant differences in Air Force and Navy performance requirements drove initially anticipated levels of commonality down, although not far enough to prevent total failure of one of the variants. The program initially started with the constraint that a single common aircraft design would be utilized for both programs. After the second of four proposal rounds, neither of the competing suppliers (Boeing and General Dynamics) had produced designs that met Navy requirements. In order to meet these requirements, the single aircraft constraint was relaxed in May of 1962 (Art, 1968), the start of the 3rd round of competition. The new approach was to allow divergence to occur in order to eliminate the Navy variant performance deficiencies. Both contractors were advised to keep divergence to the absolute minimum (TFX Contract Investigations, 1964, p. 513). Problems with aircraft variant weight and other performance metrics were significant and on-going (especially with respect to the Navy variant), even after selection of General Dynamics as the prime contractor. In mid-1964, multiple proposals were made to reduce the weight of the Navy variant design. Commonality between this revised Navy variant (F-111B) and the Air Force variant (F-111A) would have fallen from 80% to 29% based on common part number counts (TFX Contract Investigations, 1970, pp. 62-63). This path was rejected, primarily due to McNamara's emphasis on maintaining commonality.

The end outcome of the program was the production of an Air Force-only aircraft that successfully met the original TFX specification only after multiple development iterations and after the production of many inferior aircraft. The Air Force eventually procured 562 production aircraft, a much smaller number than the 1762 that had been anticipated in 1962 (Richey, undated).

[43] The TFX summary presented here is based on Boas & Crawley (2007).

The F-111B aircraft failed to meet the needs of the Navy and the Navy variant program was cancelled in July, 1968 without building any production F-111B's for operational use (TFX Contract Investigations, 1970). Direct costs associated with this cancellation were reported to be $400 million in 1969 dollars (TFX Contract Investigations, 1970), although this cost is probably insignificant with respect to the greater but less tangible impact that residual commonality (the difference between the F-111A and the Air Force-only optimized design that could have been created had an independent approach been pursued) had on the remaining variant: the Air Force accepted performance penalties that would not have been accepted if the Air Force had pursued independent development of its own aircraft. These penalties were originally believed by certain team members to have been justified for the sake of commonality and the expected cost benefits such as shared economies of scale in production and common logistics. The reality is that these benefits never materialized. The F-111A design was compromised in order to remain common with a second variant (the Navy's F-111B) that had a lifecycle demand of zero production units. Time, money, and effort were spent pursuing commonality that was never realized. The Air Force received a severely compromised design at a much higher cost in comparison to an independent aircraft program. Senator McClellan of the investigating committee sums up the problem and the heavy-handed retention of commonality that was likely the main flaw of the TFX program:

> *"…the original decision, the concept that we are going to make 80 percent of the parts common and build planes for all these missions…I don't believe anyone can say that was a proven judgment. I don't think it was practical to begin with, and I think it was proven to be impossible. As a result of not having sacrificed commonality when it was necessary to do so, you have a failure in one of the planes, a complete failure, because you got no weapon out of it." (TFX Contract Investigations, 1970, p. 188)*

One may be tempted to dismiss the TFX program as an extreme example of a historical military program with little relevance to present day development of commercial products. While arguments can certainly be made for differences between commercial and military development, the similarities with respect to commonality and divergence are greater than the differences. The TFX program had multiple customers, each of which had a specific set of requirements and the desire for an uncompromised solution with respect to these requirements. The provider (Secretary of Defense) was motivated to meet a minimal set of each customer's performance needs, while also minimizing the cost associated with doing so. Additionally, Secretary of Defense McNamara's near blind pursuit of commonality may be equated to present day executive interest that is sometimes overly strong. The result in these cases, as with the TFX, may well be the incurrence of a commonality penalty, rather than a commonality benefit.

5.4. Chapter Summary

This chapter presented a description of divergence and a presentation of some of the case evidence that supports the existence of divergence in practice. Important to the description is the fact that divergence may be either beneficial or non-beneficial and differentiating between the two is critical for improving product family profitability. Beneficial divergence trades the originally planned (real or perceived) benefits of commonality for other improvements associated with uniqueness. Non-beneficial divergence has negative cost implications for product family lifecycle costs. For example, divergence is likely to increase development costs because Intended Common elements are not leveraged across multiple products. In terms of manufacturing costs, Intended Common elements that do not actually become common incur a capability penalty that is not offset by shared economies of scale and learning.

The cost implications of divergence are intertwined with lifecycle offsets and with the general benefits and penalties of commonality. For this reason, a more rigorous treatment of the impact of divergence on the cost benefits and penalties of commonality is held until Chapter 6. A significant portion of Chapter 6 is devoted to the presentation of a simple economic model of platform-based product families and a key factor in that model is divergence.

The managerial implications of divergence are also intertwined with lifecycle offsets and with the model observations. A discussion of the management implications of divergence is held until Chapter 7 to avoid the repetition of similar discussions.

6. Lifecycle Offsets and a Simple Cost Model for Examining Commonality

Product lifecycle offsets, or the temporal relationships between the lifecycle phases of product family members, have the potential to significantly influence the relative benefits and penalties of commonality with respect to the alternative of independent development. This chapter provides a detailed description of product lifecycle offsets that focuses on the development and production phases of the product family lifecycle. The descriptions of each lifecycle phase begin with the parallel case which is then followed by the sequential non-overlapping and sequential overlapping cases. The parallel case is often implicitly or explicitly assumed in the literature, while the sequential cases were observed to be the norm in the seven complex product family case studies. A simple cost model is utilized throughout this chapter to illustrate some of the critical relationships identified during the case studies in a more rigorous manner than could have been communicated with prose alone. The simple cost model addresses the broader topic of the benefits and penalties of commonality, given lifecycle offsets and a number of other factors that are described within this chapter. Given this, the model discussion is broader in scope than the lifecycle offset topic.

6.1. Description

6.1.1. General Framework

"Offset" refers to the temporal relationships between the lifecycle phases of different product variants. The general case is illustrated in Figure 55. In order to simplify the discussion in this dissertation, each lifecycle phase is assumed to have the same duration for all product family members. With this assumption, "offset" can be utilized to describe the offset between any two equivalent lifecycle phases. For example, the offset between the starts of Product A and B development is equivalent to the offset between production starts for Product A and B. Without the assumption of constant phase durations and relationships, discussion of offsets gets very messy, yet little explanatory power is gained for the purposes of this dissertation. Future work that examines lead time would obviously need to eliminate the phase duration and timing assumptions made here.

Lifecycle offsets are a critical factor that must be incorporated into the evaluation of the planned benefits and penalties of commonality. Offsets influence a product family in several ways. First, and most basic, is the fact that future costs and benefits are discounted based on the corporate discount rate which reflects the opportunity cost of money in the context of a specific company. Second, uncertainty of future market needs and technologies combined with reduced levels of coordination between offset programs tends to lead to reduced levels of willingness or ability to pursue development of Intended Common elements. Enablement of future, less certain outcomes is passed over in pursuit of near term, more certain opportunities.

Third, offsets between the production phases of product family members reduce the potential manufacturing benefits of commonality due a loss of shared economies of scale and change the relative apportionment of the remaining benefits due to learning curve outcomes (later variants experience lower costs). Additionally, the costs of excess capability; product timing; and relative volume couple to influence the overall production benefits and penalties.

The following sections discuss development and production offsets. As mentioned previously, these two phases have been the focus of this research. A reasonable starting point for addressing operations appears to be to draw an analogy to production, although this is left to future work.

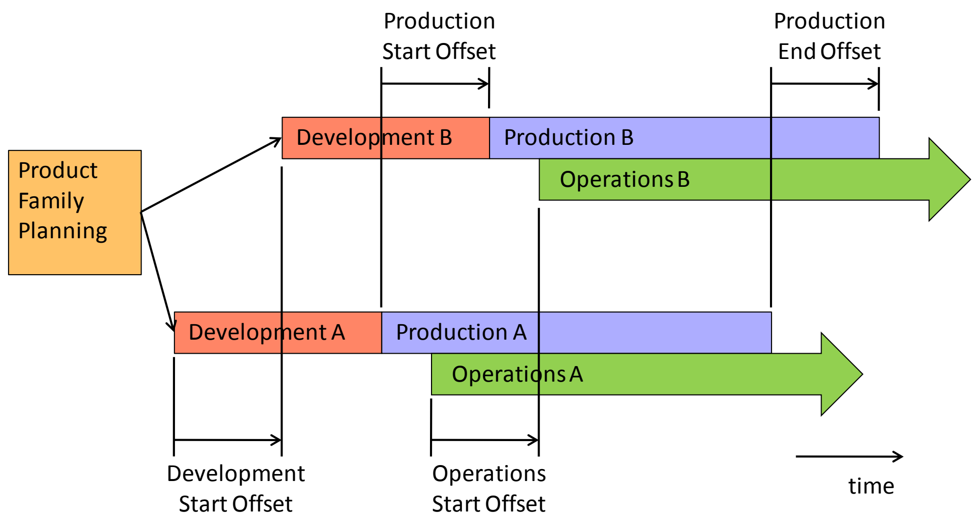

Figure 55: A two product family with offset lifecycles. For simplicity, the development and production phases of the two products are assumed to have the same duration, so the respective offsets also have the same duration.

6.1.2. Offsets in the Development of Product Variants

Product variant development can be classified into "Parallel," "Sequential Overlapping," and "Sequential Non-Overlapping" as illustrated in Figure 56. Sequential Overlapping represents the general case; the other two are limiting cases. Overlap is defined by the difference between the duration of development Program A and the offset. Parallel Development represents an offset of zero. The Sequential Non-Overlapping case represents an offset that is greater than or equal to the duration of development Program A. The case of Sequential Overlapping development represents the general case that spans all degrees of overlap between complete overlap (Parallel) and zero overlap which marks the beginning of the Sequential Non-Overlapping classification. Both types of sequential development were observed in the case studies. In terms of modeling, the two sequential development cases are treated as being the same. All development occurs at one period which is either the same or different for the two products.

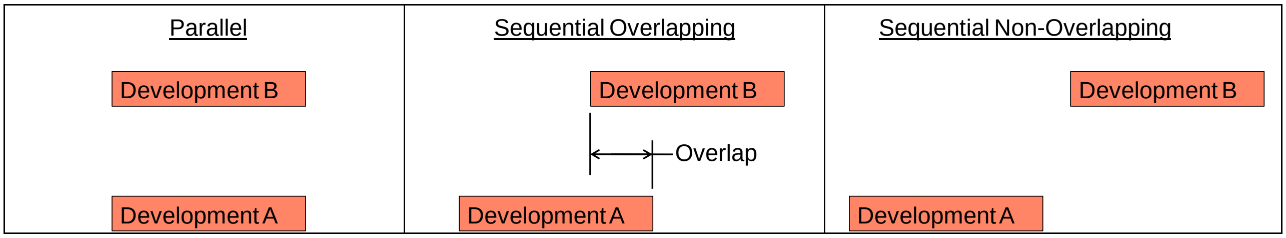

Figure 56: Parallel, Sequential Overlapping, and Sequential Non-Overlapping development classifications.

Parallel Development

Parallel development of the members of a product family represents a mode of development that appears to be commonly assumed in the literature, either explicitly or implicitly, yet was unobserved in the seven complex product family case studies associated with this research effort. Parallel development is described here as a baseline for comparison to the later sequential cases that were consistently observed during the case studies.

Parallel development consists of planning the members of the product family, followed by the simultaneous development of the products and their underlying common components. Redundant development is eliminated through the use of common components as opposed to the alternative of multiple, independently developed component versions that have similar capabilities. Figure 57 provides a conceptual illustration of the reduction in development scope that is achieved for common components. As commonality increases, total development scope reduces through sharing of components, assemblies, processes, etc.

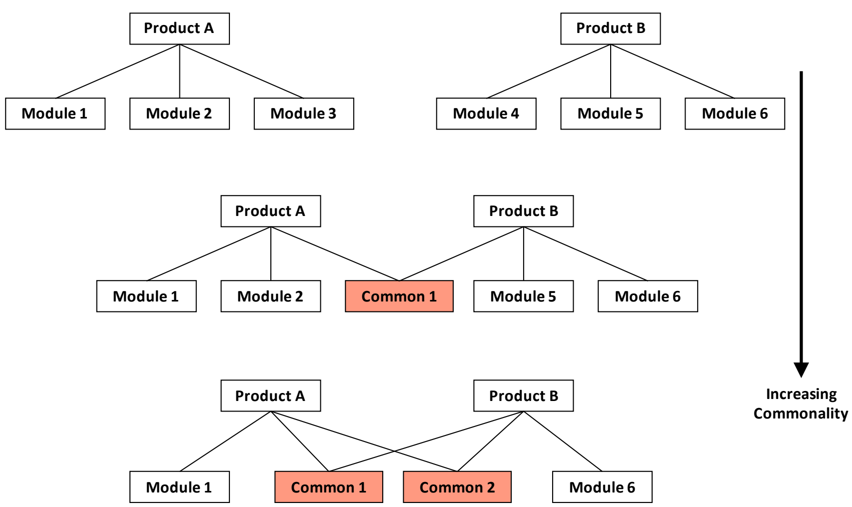

Figure 57: Development scope declines with increasing commonality. In the case of parallel development, all elements are developed concurrently.

The development scope reduction caused by commonality is partially offset by cost penalties associated with coordination and, potentially, the costs of increased development complexity. Coordination refers to the need for two or more product teams to come to mutual agreement on common component requirements (and eventually, common designs) that meet the superset of needs of the product family members or to come to the conclusion that a common component is not feasible. The resulting negotiations between teams consume resources while ensuring a good compromise is achieved between the needs of the individual product and the greater needs of the product family or that the decision to create two or more independent alternatives benefits the product family as a whole. Increased development complexity refers to the potential for development of common assets to be more complex than development of a single independent alternative.

The parallel development mode enables improved decision making effectiveness with respect to commonality because decisions are examined and implemented from the product family perspective. The decision making process consists of balancing between the potential cost benefits of commonality and the needs of the individual products, mainly the need for differentiation which is expected to increase revenue. Figure 58 illustrates the interconnection between teams representing the interests of the individual products and the platform and unique design classifications that support creation of the products. Each individual product program is staffed and is able to understand, represent, and defend its own set of product requirements. A healthy tension exists between the products ensuring tough decisions about commonality are addressed. One outcome may be the decision to pursue commonality, in which case a common design is jointly determined. The negotiation process associated with this design is aligned with the mutual adjustment concept presented in Cusumano & Nobeoka (1998). A second outcome may be the decision to pursue unique designs. Assuming that commonality is adequately considered and properly managed, the outcome of parallel development should be the identification and implementation of a set of beneficial opportunities for commonality when viewed from the perspective of the product family.

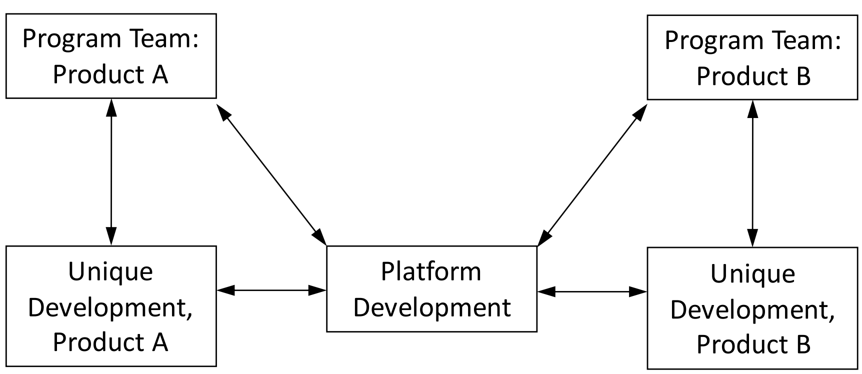

Figure 58: Parallel development of the members of a product family results in a healthy tension between the needs of the individual variants and the establishment of a common platform.

Parallel development of product family members and their underlying common elements produces net development cost savings when commonality opportunities are properly selected and managed. Parallel development is described below by using three of the five component classes described in Chapter 2: $IU_A \rightarrow U_A$ (Class 1), $IC \rightarrow C$ (Class 4), and U_B (Class 5). (Refer to Figure 59.) The assumption here is that development is all new and that outcomes follow initial plans; i.e., that reuse of Intended Unique components, $Reuse_{IU}$ and divergence, Div, are both equal to zero. Intended Common components are assumed to incur a development penalty, pen_{dev} due to the costs of coordination and complexity described above. This penalty is also assumed to include any costs of integrating the common elements into one of the products. Integration of the common elements into any product beyond the first requires the payment of an integration penalty, pen_{int}. The Product A and Product B development costs are listed in Table 6 for each of the three relevant classifications. Costs are based on the scope equations provided in Chapter 2, Figure 8. All expenses at Time 1 are assumed to be immediate, allowing the discount rate to be ignored.

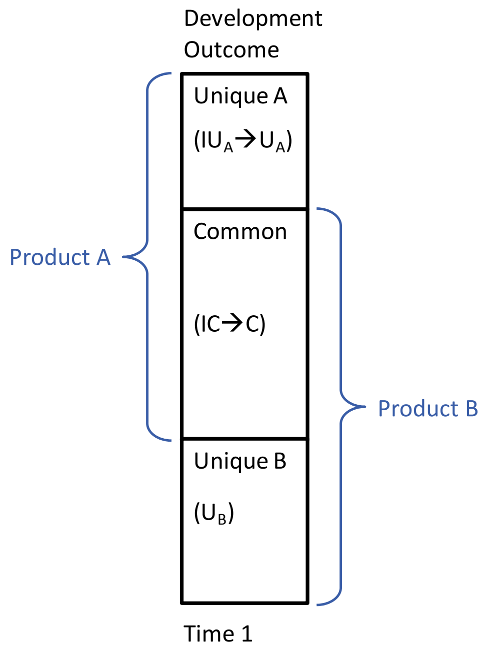

Figure 59: Parallel development of two products with commonality produces components that are unique to Product A, unique to Product B, and common to products A and B. (Derived from Figure 8 in Chapter 2.)

Table 6: Development costs are determined by scope (refer to Figure 8, Chapter 2), development penalty, pen_{dev}, and the integration penalty, pen_{int}, for the case of parallel development. Reuse of Intended Unique components and divergence are both excluded from this simple case.

Class	**Class Desc.**	**Product A Development Cost (Time 1)**	**Product B Development Cost (Time 1)**	**Benefit (Penalty) of Category Relative to Independent Alternative**
1	$IU_A \rightarrow U_A$	$(1 - COMM) * C_{dev,ind,A}$	0	Baseline
4	$IC \rightarrow C$	$COMM * C_{dev,ind,A} * [1 + pen_{dev}]$	$COMM * C_{dev,ind,A} * pen_{int}$	$COMM * C_{dev,ind,A} * [1 - pen_{dev} - pen_{int}]$
5	U_B	0	$C_{dev,ind,B} - COMM * C_{dev,ind,A}$	Baseline

The Class 4 components provide a development cost benefit when the penalty associated with developing and integrating the common components is outweighed by the benefit of avoiding development of multiple independent components. For a two product family, this means that the cost penalty of developing the new common components and the cost penalty of integrating these components into the second product, Product B, must be less than the costs of developing two independent alternatives to the common components. The condition for a two product family is

$$[pen_{dev} + pen_{int}] < 1 \tag{6.1}$$

The magnitude of the development benefit (or penalty) is assumed to be based on the degree of commonality and the cost of the independent alternative:

$$COMM * C_{dev,ind,A} * (1 - pen_{dev} - pen_{int}) \tag{6.2}$$

Development costs for the product family, $C_{dev,AB}$, can be described as a benefit or penalty added to the development cost of the independent alternatives, as illustrated in Equation 6.3. The bracketed term represents the benefit/penalty associated with common development. As the penalties associated with common development and integration rise, the benefits of the platform-based approach fall in relation to that of independently developed alternatives; all else being equal.

$$C_{dev,AB} = C_{dev,ind,A} + C_{dev,ind,B} - \left[COMM * C_{dev,ind,A} * (1 - pen_{dev} - pen_{int})\right] \tag{6.3}$$

In the parallel view that is often presented in the literature, commonality is assumed to be determined and then implemented to plan. Divergence and reuse of Intended Unique elements appear to be underemphasized in the literature as was discussed in Chapter 2 and were intentionally excluded from the equations used here to describe the costs of parallel development. Figure 60 illustrates an example comparison between two, two-product families: two independent designs and two designs based on a common platform. This example assumes independent product development costs ($C_{dev,ind.,i}$) of one unit for each product, commonality (COMM) equal to 50%, a common development penalty (pen_{dev}) of 20%, and a common integration penalty (pen_{int}) of 10%. Additionally, all development charges are assumed to be incurred immediately, allowing discounting to be ignored. While the specific example of Figure 60 illustrates a development cost savings, scenarios may exist in which a total product family development cost increase results. Regardless, of the net development cost increase or decrease, the outcome must be considered in the greater context of the overall impact of commonality on product family profitability. For example, a development cost penalty associated with commonality may provide an overall lifecycle profit increase or decrease.

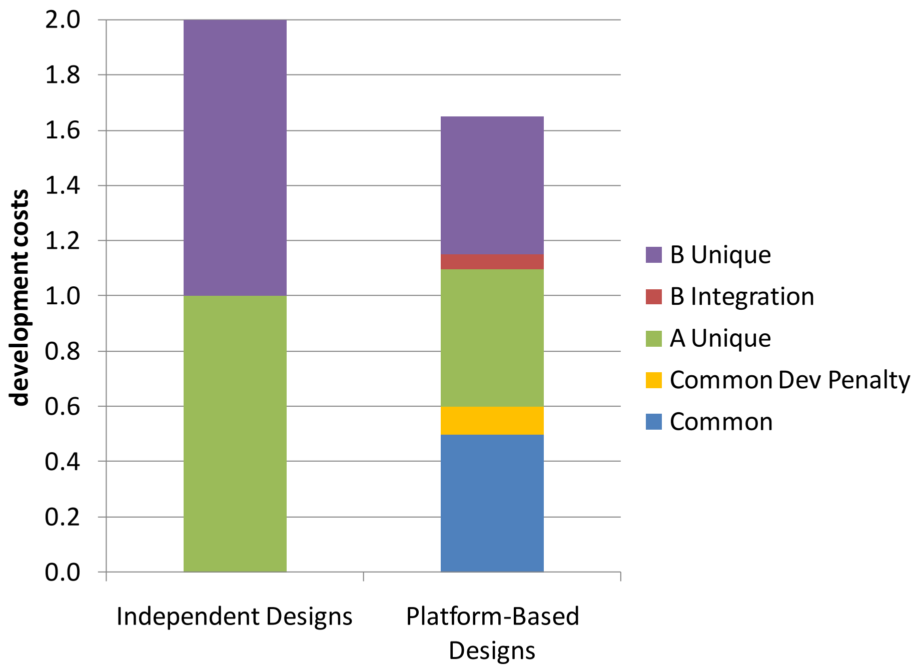

Figure 60: Total product family development cost comparison example for independent development (left) and platform-based development (right) of a two product family. Assumptions: independent development costs ($C_{dev,ind,,A}$ and $C_{dev,ind,,B}$) of 1 unit per program; 50% common ($COMM$=0.5); common development penalty (pen_{dev}) of 20%; integration penalty (pen_{int}) of 10%. Integration charges for Product A are included in pen_{dev}. This assumption simplifies later discussions of sequential development. Immediate expenses mean that the discount rate is irrelevant.

Sequential Development: A Simplistic View

Sequential Development entails the development of product variants at different points in time, rather than at the same time as was the case with Parallel Development. In the simplistic view presented in this section, the initial plan for commonality is created, then implemented as planned. Figure 61 provides a two product framework that is a simplified version of the five class version of Chapter 2. All Intended Common components developed at Time 1 become common after development of Product B at Time 2 and all Intended Unique components developed for Product A at Time 1 remain unique. The only difference in expenditures in relation to parallel development is in the weighting of future development investments for non-zero discount rates.

While total development scope does not change, the development scope is partitioned into tasks that occur at different points in time. In the case of a two-product family, development is partitioned into development that occurs in support of the first product (lead variant) and development that supports the later product (Product B; follow-on variant). For the example illustrated in Figure 62, the lead program (Product A) would develop Module 1 and Common Modules 1 and 2. The cost of developing the lead variant, $C_{dev,comm,A}$, is likely to increase with respect to the alternative of independent development (Equation 6.4) because common components are developed in place of a portion of the independent components and development of these common components is more expensive. Equation 6.4 represents one of the key disincentives for pursuing commonality as evidenced in the cases: lead programs would incur development penalties, rather than benefits, if they pursued development of common components.

$$C_{dev,comm,A} \geq C_{dev,ind.A} \tag{6.4}$$

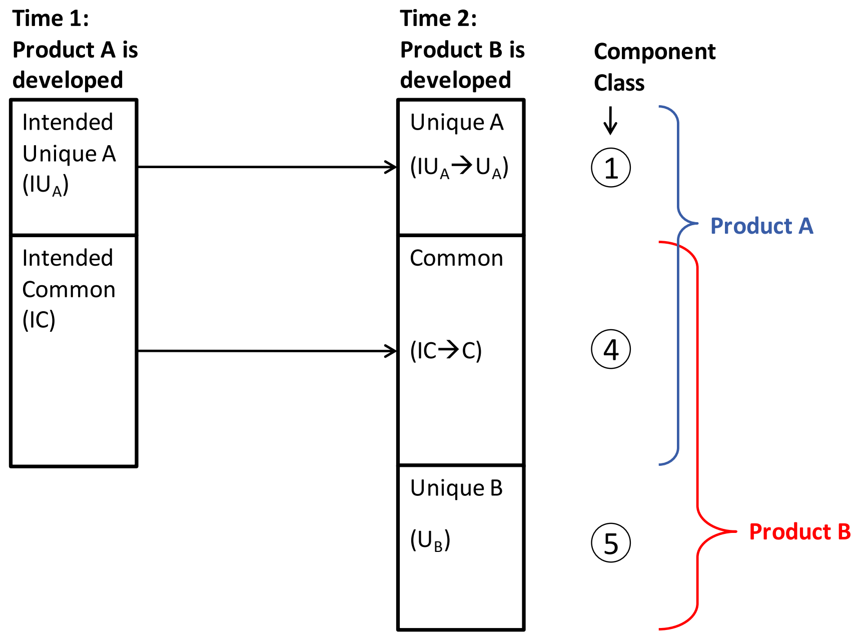

Figure 61: A simplistic view of sequential development. All Intended Common elements developed at Time 1 become Common at Time 2. The left and right columns represent the superset of components that make up Product A and Products A and B, respectively. All Intended Unique components developed at Time 1 remain Unique to Product A after development of Product B; i.e., none of the Intended Unique elements developed for Product A were reused for Product B.

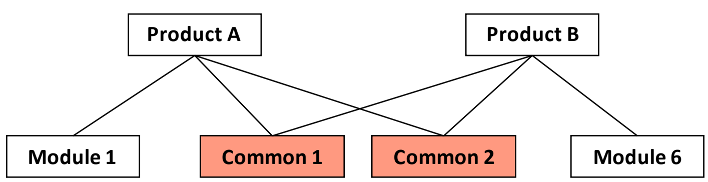

Figure 62: A two product plan for commonality. Assuming Product A is the lead variant in a sequential development setting, the lead variant development effort entails development of Module 1 and Common Modules 1 and 2. Development penalties are incurred during development of the common modules of Product A in anticipation of later reuse by Product B.

Once the lead variant has been developed, follow-on variants are created by integrating previously developed common elements with new development that is unique to each variant.

Referring back to the example of Figure 62, the follow-on program (Product B) would develop Module 6 and incur integration costs associated with integrating Common Modules 1 and 2. The follow-on variant reaps (or variants reap) the development benefits of commonality through a reduction in development scope which translates into reduced follow-on variant development costs for each variant, $C_{dev,comm,i}$, in comparison to the costs of developing the independent alternative, $C_{dev,ind.i}$ (Equation 6.5) as long as the integration penalty, pen_{int}, does not exceed the cost of new development (i.e., a value of one).

$$C_{dev,comm,i} \leq C_{dev,ind.i} \qquad \forall\ i > 1 \text{ and for } pen_{int} < 1 \tag{6.5}$$

While the above relationships, especially Equation 6.4 appear to guide individual program approaches to commonality, a discounted sum of the development costs for all variants is most important from the perspective of determination of overall product family profitability.

The simple view of sequential development can be described by the same three component classes (Class 1, Class 4, and Class 5) used to describe parallel development costs (Table 7). The differences are in the splitting of costs between two time periods and the discounting of Product B development expenses which are incurred at the later time. The subscript, r, is utilized to denote the economic discount rate and the subscript, s, denotes the offset between development programs. The relative importance of Product B development expenses decreases with increasing r and s, all else being equal.

Table 7: Sequential development costs for the relevant component classifications. The differences between this view of development and the previously described parallel view are the addition of an offset between development of the two products and a discount rate.

Class	Class Desc.	Product A Development Cost (Time 1)	Product B Development Cost (Time 2)	Benefit Relative to the Independent Alternative (negative value is a benefit)
1	$IU_A \rightarrow U_A$	$(1 - COMM) * C_{dev,ind,A}$	0	Baseline
4	$IC \rightarrow C$	$COMM * C_{dev,ind,A} * [1 + pen_{dev}]$	$\frac{COMM * C_{dev,ind,A} * pen_{int}}{(1+r)^s}$	$COMM * C_{dev,ind,A} * \left[1 - pen_{dev} - \frac{pen_{int}}{(1+r)^s}\right]$
5	U_B	0	$\frac{C_{dev,ind,B} - COMM * C_{dev,ind,A}}{(1+r)^s}$	Baseline

The relative benefit of Class 4 components is increased in comparison to the benefit associated with parallel development due to the discounting of the future integration penalty. The condition for the existence of a development cost benefit in the context of a two product family becomes

$$\left[pen_{dev} + \frac{pen_{int}}{(1+r)^s}\right] < 1 \tag{6.6}$$

In the case of simple sequential development, the development costs of the individual product variants (Equations 6.7 and 6.8) become significant in addition to the costs associated with the product family (Equation 6.9). The case studies strongly emphasized the focus on decision making at the level of the individual product. As soon as offsets are introduced into development, the lead variant (Product A) is faced with a development penalty that may provide future returns *to another program*. While a net benefit may exist at the product family level, the penalty faced by Product A's development team represents a barrier to adoption of a platform-based approach, when compared to an individual product decision making perspective. Development cost penalties and benefits are summarized in Table 8 for the simple sequential case.

$$C_{dev,A} = C_{dev,ind,A} + COMM * C_{dev,ind,A} * pen_{dev} \tag{6.7}$$

$$C_{dev,B} = \frac{C_{dev,ind,B}}{(1+r)^s} - \frac{COMM * C_{dev,ind,A}(1-pen_{int})}{(1+r)^s} \tag{6.8}$$

$$C_{dev,AB} = C_{dev,ind,A} + \frac{C_{dev,ind,B}}{(1+r)^s} - COMM * C_{dev,ind,A} * \left[1 - pen_{dev} - \frac{pen_{int}}{(1+r)^s}\right] \tag{6.9}$$

Table 8: The development benefits and penalties of commonality with respect to the independent development alternative. Product A incurs a penalty. Product B is likely to realize a benefit given that the integration penalty, pen_{int}, is likely to be less than one. A benefit at the product family level is less certain.

Product	Development Cost Benefit?	Benefit Relative to the Independent Alternative (negative value is a benefit)
A	Penalty	$COMM * C_{dev,ind,A} * pen_{dev}$
B	Trade	$\frac{-\ COMM * C_{dev,ind,A}(1-pen_{int})}{(1+r)^s}$
AB (family)	Trade	$-COMM * C_{dev,ind,A} * \left[1 - pen_{dev} - \frac{pen_{int}}{(1+r)^s}\right]$

A stylized example of simple sequential development outcomes is illustrated in Figure 63. The only difference between this example and the parallel development example is the addition of a two year offset between development of Product A and development of Product B and in the use of a 15% economic discount rate, r. In this example, an upfront development cost increase (10% over the cost of developing Product A in an independent manner, $C_{dev,ind,,A}$) is paid in order to create Product A based on a common platform. The expectation is that this additional development cost will be overcome by the future benefit of Product B development savings. In this example, the Product B development cost reduces by 45%. Total discounted costs for developing the platform-based product family are 14% lower than the alternative of developing two independent products.

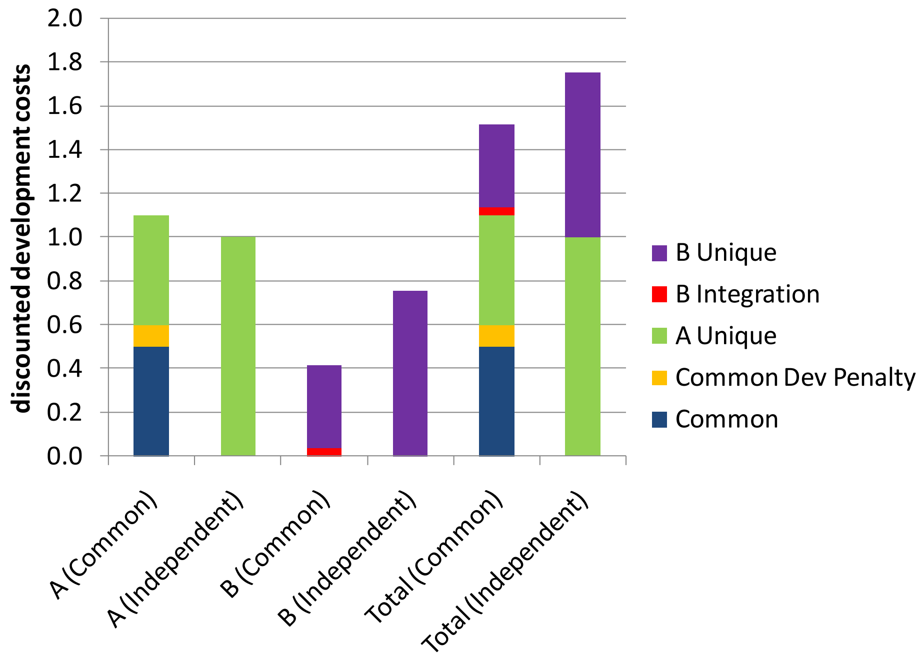

Figure 63: Example of sequential development for common and independent product strategies. Note the upfront penalty (total cost for A Common > A Independent) and future savings (B Common < B Independent). The two rightmost columns indicate the total costs for developing the two-product family. In this example, commonality produces a net development cost benefit (14%). (Assumptions: 2 year offset, s; 15% economic discount rate, r; development costs ($C_{dev,ind,,A}$ and $C_{dev,ind,,B}$) of 1 unit per program; 50% intended (and actual) common, $COMM$; common development penalty, pen_{dev}, of 20%; integration penalty, pen_{int}, of 10%.)

The simple sequential case described above highlights the potentially critical impact of time offsets on a company's perspective on the benefits and penalties of commonality. Parallel development represents the potential for a near term development cost savings while simple sequential development represents a near term penalty that is incurred in order to realize future benefits. As is described in the next section and as was illustrated in the case study findings, realization of the future benefits of commonality is uncertain.

Sequential Development: An Extended View Based on the Case Study Findings

The case studies were utilized to test the initial parallel/simple sequential framework. In both instances of the framework, commonality is defined during an upfront planning phase, then implemented to plan as the product variants are developed in either a parallel or sequential manner. Additionally, the phenomenon of divergence had been formulated as a potential outcome of common development. Divergence was hypothesized as increasing with time, meaning that divergence would have more of an impact in sequential development situations. Several key case findings with respect to lifecycle offsets in complex product families are described below. Key aspects of the findings are then incorporated into a refined model of development costs.

The members of complex product families are developed sequentially, an outcome driven primarily by resource limitations but also influenced by both market uncertainty and technological capability. While this point was discussed in Chapter 4, it is a critical observation:

complex products are developed sequentially, rather than in parallel. All the cases followed a sequential development strategy with varying degrees of overlap. This approach enabled the companies to manage resource requirements, limit exposure to market uncertainty, and in some cases (e.g., military aircraft), build technological capabilities that were required to produce later variants. Several case examples are listed below:

- **Case A:** The automotive company developed a product family plan for two products and designated common elements. These elements were then developed alongside the lead (SUV) variant, with the intent of being utilized to create a follow-on (truck) product two years later.
- **Case B:** The military aircraft program pursued a strategy of parallel development of three aircraft concepts through preliminary design, followed by sequential development beyond that point in order to control resource requirements. The layout phases for each variant started approximately 6 months apart.
- **Case C:** The commercial aircraft company developed a product family plan and early preliminary designs for three major variants and then transitioned to the development of one variant at a time as resource requirements increased. The variants were started approximately one year apart and took three to four years to develop.
- **Case E:** The printing system company had a consistent strategy of developing new product features in its high volume (and revenue) product line, followed by leveraging of these new developments in its other product lines. Product development offsets ranged from almost zero to several years.
- **Case G:** The semiconductor manufacturing equipment company followed a similar strategy of focusing development resources on the high volume product line, followed by later usage in its other product lines. The semiconductor manufacturing equipment case did provide one notable exception to the sequential development hypothesis for complex products: three closely related products were developed simultaneously during a recent product development effort. The decision to create three products simultaneously was driven by the need to respond to a competitive situation that was creating downward pricing pressure on Company G's existing products. The three products allowed Company G to cost-effectively and quickly provide varying capabilities at varying price points.

Aside from the partial exceptions of the printing press and semiconductor manufacturing equipment cases, the case studies suggest that parallelism is limited to product family planning and preliminary design efforts within the domain of complex product families. The parallel approach that seems to be implemented in the development of simpler products such as the Black & Decker hand tools described by Meyer & Lehnerd (1997), was not observed within the seven cases.

The sequential nature of complex product family development appears to be driven by several factors. First and foremost is an organization's need to manage resource requirements (e.g., overall product investments, headcount, lab facility utilization, etc.). Resource requirements were cited in each case study as being the primary driver for sequential development, as companies often attempt to maintain relatively level requirements. Developing product variants in a sequential manner flattens resource requirements in comparison to a large all-at-once development effort that requires a much larger peak resource requirement, followed by a lull. This is especially important in organizations that produce few products. For example, new military aircraft programs are not frequent enough to support teams that are able to develop multiple variants simultaneously. A company with the capability to develop multiple products simultaneously (e.g., an automotive company) may choose to develop those products within the same product family, although this outcome was not observed in the case studies, less the previously noted exceptions.

A second factor, market uncertainty, also plays a potential role in a company's decision to pursue sequential development of its product models. A product can be viewed as a market "test," with findings from the market test being incorporated into later variants. This explanation ultimately ties back to resource limitations: without resource limits, an organization will create many "tests" (products). Market uncertainty appeared to be much less important than resource management for the cases studied as part of this research. While market uncertainty may be a minor factor in the decision to pursue sequential development, this uncertainty is a major factor in a company's ability to implement initially planned commonality as evidenced by the discussion of divergence.

A third factor concerns technology limitations. Given an evolving technology and a plan for a family of increasingly capable products, a company may not have the technical capability to develop all the members of its product family at once. Incremental technological advancements may be needed to enable the company to create other, more capable variants. The military aircraft, printing, semiconductor manufacturing equipment, and satellite cases all illustrate the role of advancing technologies. The military aircraft program provides a good example, as the Conventional Takeoff and Landing variant was selected as the first variant primarily because it was the "easiest" variant to develop. Technological advancement was less of a factor in more mature product lines, such as the automotive, commercial aircraft, and business jet cases. This is not to say that new technologies were not developed for these variants, but that differences between the variants did not create significant technological challenges that drove the need for development of the variants in an "easy" to "hard" order.

The case studies point toward a view of sequential development that relies less on predicting and acting upon the future and more on reusing from the past. Commonality results from reuse of prior development that was originally intended to meet the needs of another product. From the perspective of an individual product, reuse of previously developed assets, whether they were developed as Intended Common or Intended Unique, represents the efficient utilization of an organization's resources; reduces lead time; and may reduce risk. As observed in the case studies, current development programs leverage past designs as baselines with elements of these baselines being carried forward either directly or in a modified form. For example, the follow-on variant (truck) in the automotive case utilized the lead variant (SUV) as a baseline along with a prior model year truck. The fighter aircraft example also relied heavily on the modification of prior baselines: the CTOL variant served as the baseline, with both the STOVL and CV variants being developed through modification of this baseline. Reuse and modification ensure efficient utilization of the resources of the current program and do not overly constrain designs: if preexisting elements are not adequate, the alternative of new development always exists and is justified in order to meet the needs of the current program.

Within the case study programs, a much lower degree of emphasis was placed on taking development actions that could have been beneficial to future products and for the product family as a whole (i.e., Intended Common development). Doing so requires additional investments to be made during lead variant development in the pursuit of future benefits that are both uncertain and discounted. From the perspective of the lead variant, these penalties are unattractive as they provide no development benefit back to the lead variant. The lack of benefit to the lead program, coupled with the observed lack of multi-product cultures and management, suggests that true proactive approaches to enabling future commonality (i.e., pursuit of Intended Common development) have a limited likelihood of being pursued in industry. This was certainly the finding of the seven case studies. This result was surprising based on the review of the platform literature. Clearly, the upfront penalties combined with other negatives such as potential manufacturing cost increases, high coordination costs, and the potential for revenue impacts have limited the degree to which platform-based development is applied in the context of complex product families. The exceptions to the above statements are the common building block programs that were described in Chapter 4.

Prior products are used as baselines for each development program and the companies place little weight on whether or not prior development was Intended Common or Intended Unique. While this dissertation differentiates between Intended Common and Intended Unique elements, very little differentiation was observed in industry. Elements may be developed as Intended Common or Intended Unique, but future programs have no reason to differentiate between reuse of Intended Common or Intended Unique elements. Only one out of the seven case study product families (military aircraft) tracked common parts during development, meaning that determination of original design intent is only possible through the memories of individuals involved in the programs. The prevailing approach observed in the case studies is the use of prior products baselines as starting points for new product development efforts (Figure 64). While a reasonable hypothesis would be that development of Intended Common elements produces higher levels of beneficial commonality through a better match with future product needs, this is not a given and was certainly not proven by this research effort.

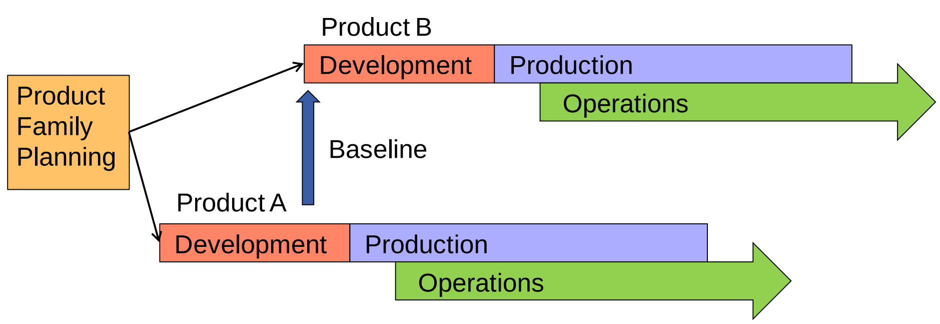

Figure 64: Baselines are often carried forward from prior models, an outcome driven by the need for efficiency.

The sequential development histories of the case studies provided limited evidence of the existence of the tension that is required to establish common component designs. The outcome is a reduction in the degree and costs of coordination and, as a result, a reduction in the level of Intended Common development. Tension between two or more product models, such as the tension suggested in the parallel development description, ensures that trades associated with commonality are examined and that they are made in the best interests of the product family. Without this tension, decisions are skewed towards the needs of the individual variants, an outcome that may result in non-beneficial total development cost increases.

In the case of sequential development, all variants are not represented by fully staffed (and funded) program teams. During development, the lead variant has a fully staffed team and a sense of urgency around decision making: an immediate need exists for the product. Follow-on variants represent future, less certain opportunities. Given resource limitations, organizations do not staff these future programs to the same level as that of the current program: staffing current programs represents a more "certain" opportunity.

Figure 65 shows a conceptual organization charged with developing the lead variant in a two product, sequentially developed family. The organization consists of two product teams, each of which is charged with creating an individual product based on a common platform. Product A represents the lead variant and is fully resourced to support development of both the Intended Common ("platform development") and Intended Unique elements. Product Team B is minimally staffed, at best. Product Team B may or may not participate in the design of the common elements in order to improve the match between the Intended Common elements and the anticipated needs of Product B. The needs of Product B are less certain than Product A and Product B has a limited ability to engage in development due to resource limitations. As a result, the Intended Common elements created by the Product A team are skewed towards the more certain and better represented needs of Product A. Once Product A has been completed, resources become available to develop Product B. At this point, Product A is in production and is not involved in Product B's development decisions. (Refer to Figure 66.) Program B modifies the Intended Common elements to meet the needs of Product B, resulting in divergence from the initially planned levels of commonality.

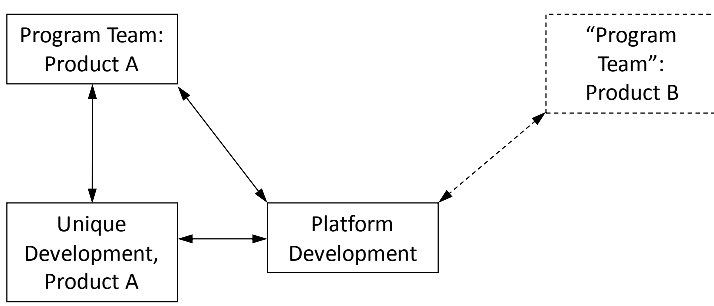

Figure 65: A conceptual view of key interactions between two product teams in the context of lead variant development. Initially, Program A (the lead variant) is fully staffed and drives development of the Intended Unique and Intended Common ("Platform Development") elements associated with its needs. Limited to no representation exists from the follow-on variant, Product B, creating a lack of tension between the needs of the two products when making decisions about intended commonality. The platform is skewed towards the immediate needs of the lead variant.

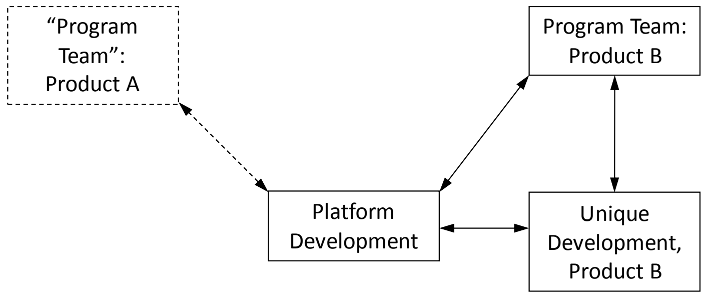

Figure 66: A conceptual view of key interactions between two product teams in the context of follow-on variant development. The lead variant, Product A, is in production or readying for production and is not engaged in the development of the follow-on variant, Product B. Product B faces a mismatch between its needs and the previously developed Intended Common elements. Program Team B modifies the previously developed Intended Common elements to meet its needs and commonality is reduced as a result.

The automotive case description in Chapter 4 provides a good example of this lack of tension. Intended Common development occurred within the SUV (lead variant) development program. At that time, the truck development team was working on developing earlier model year vehicles and could not participate in the development of Intended Common components to the same extent as the SUV team, which had an immediate need. The resulting lack of tension led to skewing of Intended Common components towards the immediate needs of the SUV team and away from the less certain needs of the truck team. To the extent that development penalties or production penalties associated with excess capability were incurred by the SUV, a development cost increase resulted without an offsetting benefit. In some instances, the truck team chose to develop new Intended Common elements that are planned for use in future SUV's, indicating that common designs were sometimes possible, had both vehicle programs had the resources to allow for an increased level of overlapped design and negotiation.

From the standpoint of development costs, the above discussion suggests that two factors must be incorporated into the simple sequential development model of the previous section: the impact of divergence on the degree of reuse of Intended Common components and the benefit of reusing Intended Unique elements (Figure 67). Both appear to be underemphasized in the existing literature, yet the seven case studies suggest that they are critical. Divergence, Div, increases development costs through the need to repeat development of previously Intended Common elements. Reuse of Intended Unique elements, $Reuse_{IU}$, reduces development costs through leveraging previously developed components that were not intended to be common with a future product. Referring back to the two product framework, two additional links and component classes have been added that were not present in the simple sequential description of Figure 61.

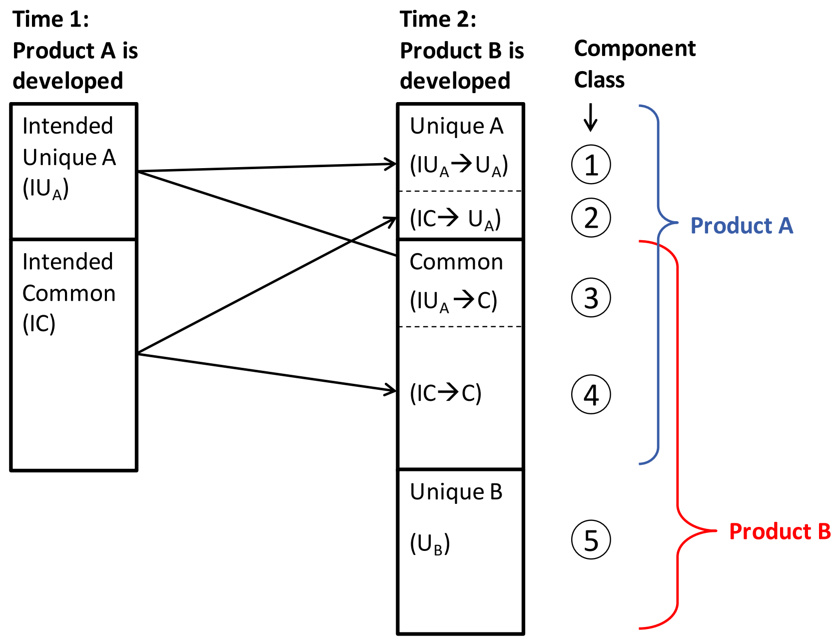

Figure 67: The sequential development description based on the case studies has five component classifications. Often overlooked are the potential for Intended Common elements to become Unique (IC→ U_A) and for Intended Unique elements to become Common (IU_A →C).

The equations describing the development costs of the five component classes are listed in Table 9. The total costs are computed by multiplying the cost basis (column 3) with the summation of the Product A and Product B multipliers (columns 4 and 5, respectively). The net development benefit or penalty for a given class is determined by subtracting the total development cost for a given category from the discounted summation of the independent alternative costs for Products A and B. The table indicates that a development benefit is never realized for Class 2 components: penalties are incurred pursuing commonality that never provides a development scope reduction for the follow-on program. Class 3 components, those that are intended to be unique but that are reused by Product B, represent a class of components that is always likely to provide a development cost benefit. For Class 3, the benefit condition is simply that the cost of integrating the Intended Unique components into the Product B design is less than the cost of developing new components. Class 4 components, those that are intended to be common and actually become common, are subject to a trade: the development cost penalty must be offset by the discounted future development benefit, less the discounted costs of integration.

Table 9: Costs of the five component classes for the extended sequential development description.

Class	Class Desc.	Cost Basis ("basis")	Product A Multiplier (Time 1)	Product B Multiplier (Time 2)	Benefit Relative to the Independent Alternative (negative value is a benefit)
1	IU_A→U_A	$(1-COMM) * C_{dev,ind,A} * (1-Reuse_{IU})$	1	0	Baseline
2	IC→ U_A	$COMM * C_{dev,ind,A} * Div$	$(1+pen_{dev})$	0	$basis * [pen_{dev}]$

3	$IU_A \rightarrow C$	$(1-COMM) * C_{dev,ind,A} * Reuse_{IU}$	1	$\frac{pen_{int}}{(1+r)^s}$	$basis * \left[\frac{1-pen_{int}}{(1+r)^s}\right]$
4	$IC \rightarrow C$	$COMM * C_{dev,ind,A} * (1-Div)$	$(1+\ pen_{dev})$	$\frac{pen_{int}}{(1+r)^s}$	$basis * \left[-pen_{dev} + \frac{1-pen_{int}}{(1+r)^s}\right]$
5	U_B	$C_{dev,ind,B} - (1-COMM) * C_{dev,ind,A} * Reuse_{IU} - COMM * C_{dev,ind,A} * (1-Div)$	0	$\frac{1}{(1+r)^s}$	Baseline

If reuse of Intended Unique components is ignored, the development of Intended Common components produces a net development benefit for the product family when the combined costs of Class 2 and Class 4 components (the Intended Common components) is less than the independent alternative with reuse. Equation 6.10 provides the condition under which a net development cost benefit occurs. The development costs incurred during development of Product A must be offset by the actual reuse of Intended Common components, $(1-Div)$, less the cost of integrating these components into the Product B design. The latter term is discounted, decreasing its importance relative to the upfront development cost penalty incurred by Product A. The product of the two leftmost terms of Equation 6.10 represents the magnitude of the commonality benefit. Equation 6.11 provides a different view of the benefit condition that sets the maximum rate of divergence for a given development penalty, integration penalty, discount rate, and offset.

$$COMM * C_{dev,ind,A} * \left[pen_{dev} - \ (1-Div)\ \frac{(1-pen_{int})}{(1+r)^s}\right] < 0 \tag{6.10}$$

$$Div < 1 - \frac{pen_{\ dev} * (1+r)^s}{(1-pen_{\ int})} \tag{6.11}$$

Figure 68 illustrates a stylized example of the key trades between offset, divergence, and development penalties per Equation 6.11. The discount rate and integration penalty are assumed to be fixed at 15% and 10%, respectively. Non-zero discount rates create the downward sloping trend as offsets increase (visible in the figure). A discount rate of zero (not shown) has the effect of eliminating the downward trend with increasing offset; i.e., offset values become inconsequential. Charts such as Figure 68 may aid a company in determining its willingness to invest in commonality. For example, given an offset that is fixed by resource limitations and a rough estimate of the common development penalty, pen_{dev}, a company can consider its historical divergence levels when determining the likelihood of realizing a development benefit in the current program. (The reader is reminded that the development benefit is only one component in determining lifecycle profitability of the product family.)

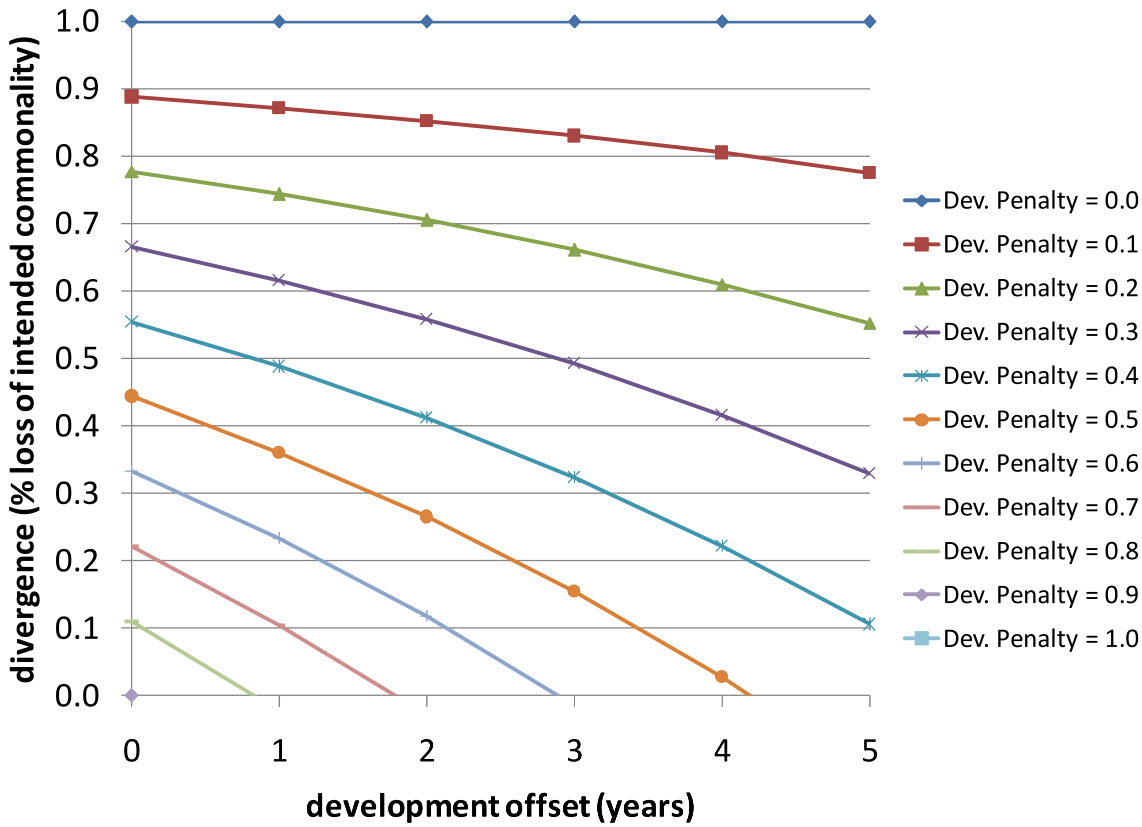

Figure 68: Decreasing rates of divergence and decreasing offsets increase the allowable development penalty for Intended Common components that still maintains a net benefit over the independent alternative. For the curve defined by a given development penalty, values of offset and divergence below the line represent beneficial conditions for the pursuit of Intended Common elements, assuming that no reuse of Intended Unique components occurs. The best case scenario is the lower left corner of the chart. (Assumptions: $Reuse_{IU}$= 0; pen_{dev}= 10%; dr= 15%.)

As indicated in the case studies, reuse of Intended Unique components, $Reuse_{IU}$ (Class 3), is prevalent in practice and must be considered along with reuse of Intended Common elements. The development benefit of reusing Intended Unique elements is well understood in practice: a cost benefit is always expected given that no penalty was paid for developing Intended Unique components during Program A and that reuse of these components during Program B creates an integration charge only: as long as the integration penalty, pen_{int}, is less than unity (given the two product example), a development savings results. While reuse requires the existence of previous, relevant designs, this was found to be true in every one of the seven case studies. Truly "clean sheet" designs are rare in practice.[44] Class 3 components represent a critical alternative to which to compare Intended Common opportunities.

[44] Even the Joint Strike Fighter program (the military aircraft case) had a high degree of reuse. While the program may seem to be a "clean sheet" approach, Lockheed Martin has heavily leveraged past experience, particularly that gained from the F-22 program. The F-35 engine is closely related to the F-22 engine and the F-35 airframe appears to benefit from similarity with the F-22 airframe.

Beyond the prevalence of reuse of Intended Unique components, the cases studies suggest that development spending on Intended Common components is significantly lower than one may assume based on a review of the platform-based development literature. In terms of the simple model presented here, the effect is a reduction of the size of the Intended Common term, $COMM$.

The benefit of reusing Intended Unique elements relative to the alternative of independent development is described by Table 9, Row 3 which is repeated below as Equation 6.12. The benefit increases with increasing uniqueness of the products; i.e., as $COMM$ decreases.

$$(1 - COMM) * C_{dev,ind,A} * Reuse_{IU} * \left[-\frac{(1-pen_{int})}{(1+r)^s}\right] < 0 \tag{6.12}$$

For later modeling purposes, reuse of Intended Unique elements is assumed to be defined as

$$Reuse_{IU} = \frac{A}{(1+\gamma)^s} \tag{6.13}$$

Where γ represents the decrease in reuse of Intended Common elements with time and A is the initial degree of reuse at time zero. Setting γ to zero holds the $Reuse_{IU}$ fraction at the initial value, A, which is assumed to be well-below unity. The actual form of this equation is unknown and may vary considerably. Further research is required in this area.

Individual product costs and the cost of the product family are listed below. Note that the development cost for Product A depends only on intended commonality and does not depend on the degree of divergence or reuse (Equation 6.14). The Product A development cost penalty depends only on the intended commonality level, $COMM$, total development cost, $C_{dev,ind,,A}$, and the penalty associated with developing these Intended Common components, pen_{dev}. Assuming non-zero levels of intended commonality and non-zero development penalties, Product A always incurs a development penalty. Product B development costs are described by Equation 6.15. Product B benefits from non-zero $Reuse_{IU}$ levels and from divergence levels that are less than one (i.e., from any reuse, regardless of original design intent), as long as the integration costs are less than the costs of new development (less than unity in this example). The product family development costs (Equation 6.16) are the sum of Equations 6.14 and 6.15. Table 10 provides a summary of the benefit/penalty portions of Equations 6.14, 6.15, and 6.16.

$$C_{dev,A} = C_{dev,ind,A} + COMM * C_{dev,ind,A} * pen_{dev} \tag{6.14}$$

$$C_{dev,B} = \frac{C_{dev,ind,B}}{(1+r)^s} - \left[COMM * C_{dev,ind,A} * (1 - Div) * \frac{(1-pen_{int})}{(1+r)^s}\right] - \left[(1 - COMM) * C_{dev,ind,A} * Reuse_{IU} * \frac{(1-pen_{int})}{(1+r)^s}\right] \tag{6.15}$$

$$C_{dev,AB} = C_{dev,ind,A} + \frac{C_{dev,ind,B}}{(1+r)^s} - \left[COMM * C_{dev,ind,A} * \left[(1-Div) * \frac{(1-pen_{int})}{(1+r)^s} - pen_{dev}\right]\right] - \left[(1-COMM) * C_{dev,ind,A} * Reuse_{IU} * \frac{(1-pen_{int})}{(1+r)^s}\right] \quad (6.16)$$

Table 10: Summary of the product-level development benefits and penalties of commonality with respect to the independent development alternative for the extended sequential case.

Product	Development Cost Benefit?	Benefit Relative to the Independent Alternative (negative value is a benefit)
A	Penalty	$COMM * C_{dev,ind,A} * pen_{dev}$
B	Trade	$-\left[COMM * C_{dev,ind,A} * (1-Div) * \frac{(1-pen_{int})}{(1+r)^s}\right] - \left[(1-COMM) * C_{dev,ind,A} * Reuse_{IU} * \frac{(1-pen_{int})}{(1+r)^s}\right]$
AB (family)	Trade	$-\left[COMM * C_{dev,ind,A} * \left[(1-Div) * \frac{(1-pen_{int})}{(1+r)^s} - pen_{dev}\right]\right] - \left[(1-COMM) * C_{dev,ind,A} * Reuse_{IU} * \frac{(1-pen_{int})}{(1+r)^s}\right]$

Two simple examples were constructed to compare independent development to the simple sequential development case and to sequential development with divergence for a specific set of model inputs that are defined in the figure caption. Reuse was excluded in the first example (Figure 69, Figure 70, and Figure 71). Figure 69 shows a rise in Product A development costs, given the pursuit of a common sequential strategy, the existence of a common development penalty, and the other model parameters as listed in the figure. The presence or absence of divergence has no impact from the Product A perspective. (Compare the middle and right hand columns.) Figure 70 indicates a development cost reduction for Product B; a reduction that is tempered in the presence of divergence. Figure 71 provides the product family view which is simply the summation of the discounted costs of Figure 69 and Figure 70. Figure 71 illustrates the potentially significant differences between an idealized view of platform-based development that assumes Intended Common elements are implemented to plan ("simple sequential") and a more realistic view of platform-based development that includes divergence ("sequential w/divergence"). In this example, platform-based development would provide a total development savings of 14%, given a lack of divergence. The development benefit declines to an 8% savings if a 30% loss of intended commonality occurs. Figure 72 illustrates the same example with the addition of reuse of Intended Unique elements. The development cost benefit of reusing Intended Unique components applies to the Intended Unique portions of the independent and platform-based alternatives. Given that the highest proportion of Intended Unique elements is in the independent case (the entire products are Intended Unique), the presence of reuse of Intended Unique components has the effect of decreasing the relative benefit of commonality. In the example, the simple sequential development cost benefit is reduced from 14% to 11%, while the benefit for the sequential with divergence case is reduced from 8% to 5%.

The example helps to explain why divergence and reuse of Intended Unique components are critical factors that must be considered with respect to both valuing and managing commonality. Given the parameters of the example, the presence of divergence and reuse shifts the benefit of pursuing common development from a 14% total development cost reduction to a 5% total development cost reduction relative to the alternative of independent development. *Also note that while the examples illustrated here show a development benefit of pursuing common development in relation to independent development, this outcome is not a given: a development penalty could also result.*

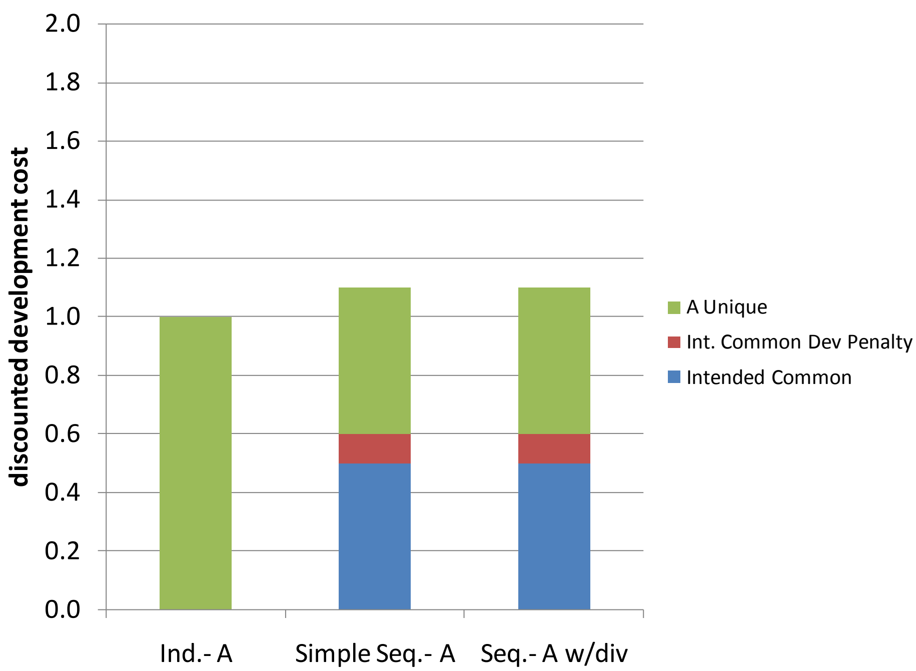

Figure 69: Product A development costs (discounted) for a two-product family, given three scenarios: independent development, simple sequential, and sequential w/divergence. Reuse of Intended Unique elements is excluded in this example. Product A is likely to realize a development cost increase given the pursuit of Intended Common development. The following assumptions are relevant to this figure, along with Figure 70 and Figure 71: 2 year offset; dr=15%; independent development costs ($C_{dev,ind,,A}$and $C_{dev,ind,,B}$) of 1 unit per program; $COMM$=50% common; pen_{dev}= 20%; pen_{int}= 10%; Divergence: Reuse$_{IC}$ is initially 100% and declines at the rate of 20% per year (31% loss of intended commonality in this example).

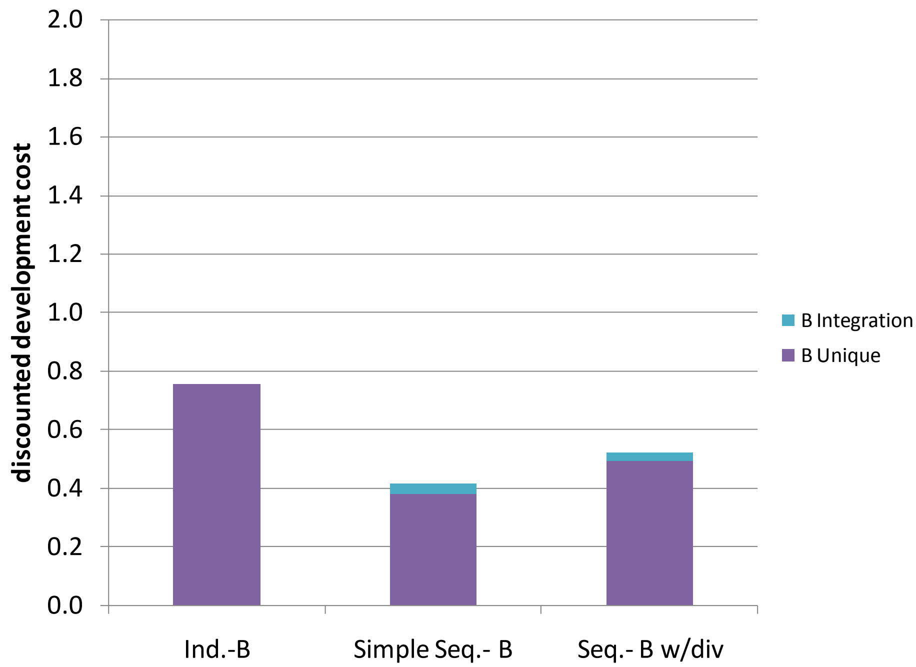

Figure 70: Product B development costs (discounted) for a two-product family, given three scenarios: independent development, simple sequential, and sequential w/divergence. Reuse of Intended Unique components is excluded in this example. Pursuit of Intended Common development may result in a Product B development cost reduction. Divergence reduces the benefit. Assumptions are listed in the Figure 69 caption.

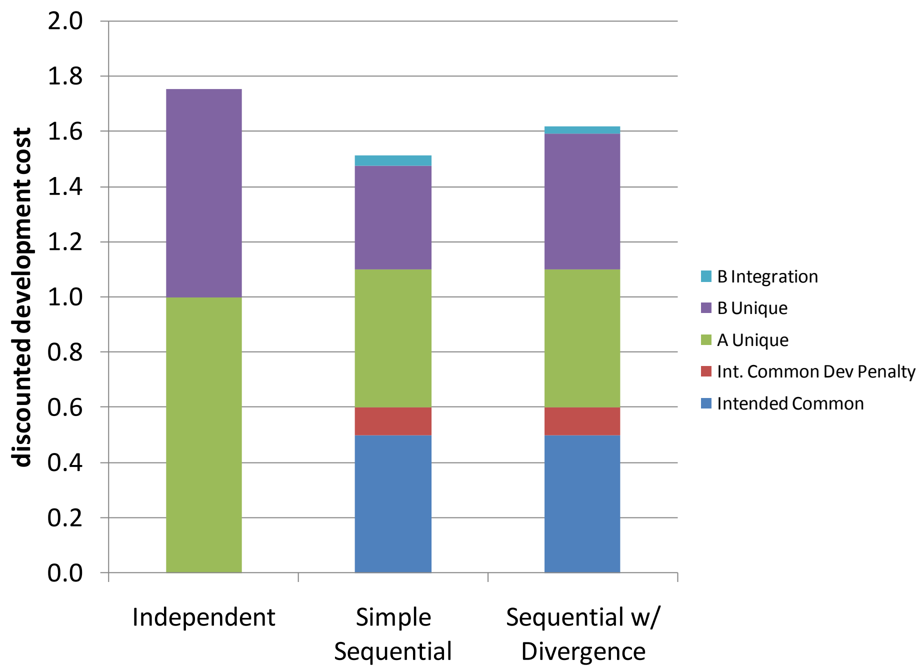

Figure 71: Total, discounted development costs for a two product family: independent, simple sequential, and sequential w/divergence. Reuse of Intended Unique components is excluded. Divergence reduces the development benefit associated with commonality due to the need to repeat development of Intended Common elements that were not utilized by Product B. Assumptions are listed in the Figure 69 caption.

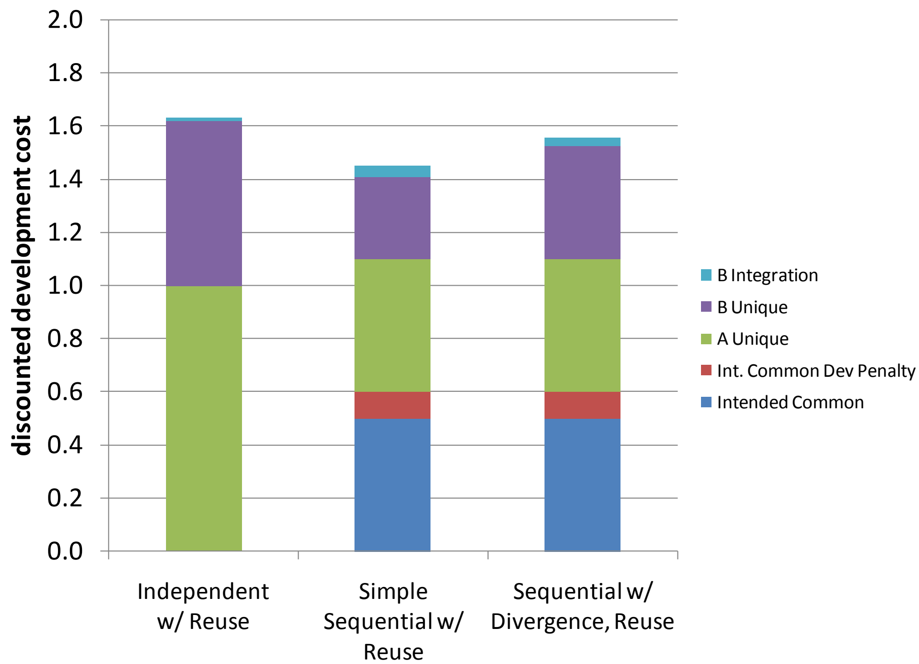

Figure 72: Development costs for a two product family: independent, simple sequential and sequential w/divergence. Reuse of Intended Unique components is included. While platform-based development costs are still lower than the independent alternative, the consideration of reuse of Intended Unique components has reduced the relative benefit. Assumptions match those listed in the Figure 69 caption with the following addition: Reuse_{IU} is initially 20% and declines at a rate of 5% per year (18% reuse of Intended Unique in this example).

The impact of lifecycle offsets on the relative development cost benefits of commonality was also examined. Figure 73 illustrates total development costs for offsets that range from zero to seven years. The relative development benefit of commonality falls with rising offsets and eventually becomes a penalty, an outcome that is driven by the fact that divergence and reuse of Intended Unique components are both functions of time. Divergence increases with offset, meaning that intended commonality declines with increasing offset. Likewise, the degree of reuse of Intended Unique components also is assumed to decline with time. The figure illustrates the decline of intended commonality (starts at 100% of Intended Common) and also the decline in reuse of Intended Unique components (starts at 20% of Intended Unique). In this example, commonality offers a benefit for lifecycle offsets that are at or below 3.5 years. *Given the assumptions of this example,* a company should reject the pursuit of Intended Common development when offsets are greater than 3.5 years. Decreasing the discount rate increases the crossover point with a discount rate of zero enabling offsets of up to approximately 5.4 years to remain beneficial.

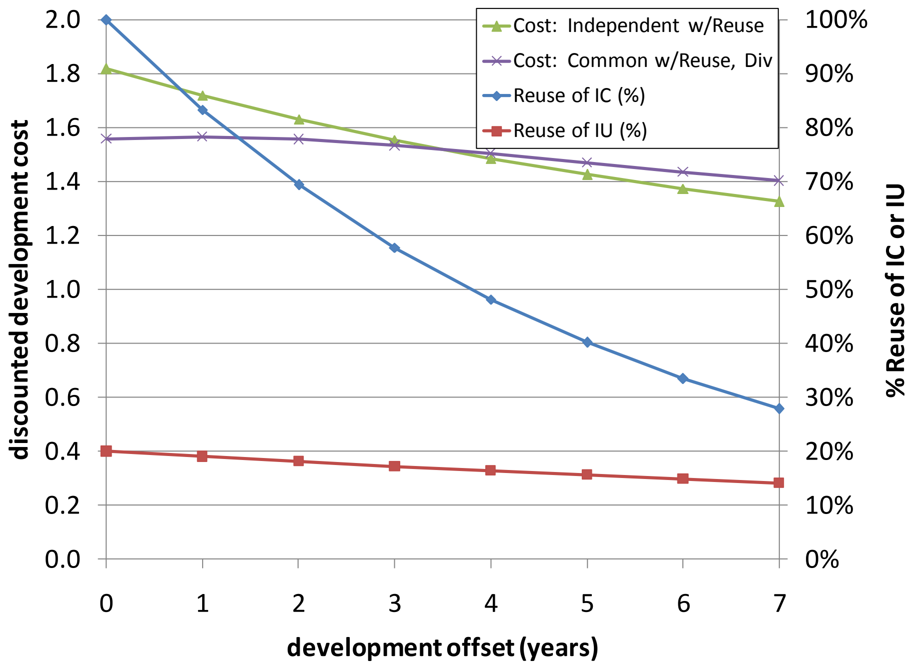

Figure 73: Comparison of total, discounted development costs as a function of development offset. In this example, sequential development is beneficial for development offsets of less than approximately 3.5 years. The independent case is influenced by the economic discount rate (15%) and temporally decreasing reuse of Intended Unique elements. The sequential case is influenced by the economic discount rate, reuse of Intended Unique components, and divergence. Percent reuse of Intended Common and reuse of Intended Unique components both decrease for increasing offsets. Refer to the Figure 69 caption for assumptions. Decreasing the discount rate increases the crossover point with a discount rate of zero enabling offsets of up to approximately 5.4 years to remain beneficial (not shown).

A key question faced by industry is whether or not Intended Common development strategies are beneficial in relation to the alternative of independent development with reuse (of Intended Unique components). Reuse of Intended Unique components (Class 3) is common in practice, while pursuit and reuse of Intended Common components (Class 2 and Class 4) appears to be less common but may produce benefits. A development trade exists between deciding to create Intended Common elements as part of the lead variant and developing Intended Unique elements that may potentially be reused during development of the follow-on variant. In terms of the classification utilized within this dissertation, the trade is a comparison between the average components costs for Classes 1 and 3 and Classes 2 and 4. The benefit of developing and reusing Intended Common components outweighs the benefits of reusing Intended Unique components when the following condition is met:

$$(1 - Div) - Reuse_{IU} > \frac{pen_{dev} * (1+r)^s}{(1-pen_{int})} \quad (6.17)$$

Equation 6.17 provides several insights into the Intended Common/Intended Unique trade. Rising development penalties, discount rates, and offsets all require lower rates of divergence in order for Intended Common development to provide a benefit relative to Intended Unique development. Increasing integration penalties (costs) provide a relative benefit to intended commonality but decrease the overall benefits of both reuse strategies with respect to new development. (The latter point is evidenced by an inspection of Equation 6.16, for example.) Figure 74 illustrates the key trades. "Reuse IC" indicates the reuse of Intended Common components and is equivalent to one minus the degree of divergence. For a given development penalty, all offset and divergence combinations below the respective line represent conditions under which pursuit of intended commonality is favorable to reuse of Intended Unique components. This chart indicates the relative benefits of the two reuse strategies. Comparisons must also be made to the alternative of developing new components, as described by the terms in Equation 6.16, for example. Assuming the existence of a benefit over the independent alternative, the relative development benefit of one strategy over the other is one factor that should be considered in determining the value of commonality. It is important to emphasize that both Intended Common and Intended Unique development are likely to occur to some degree in practice.

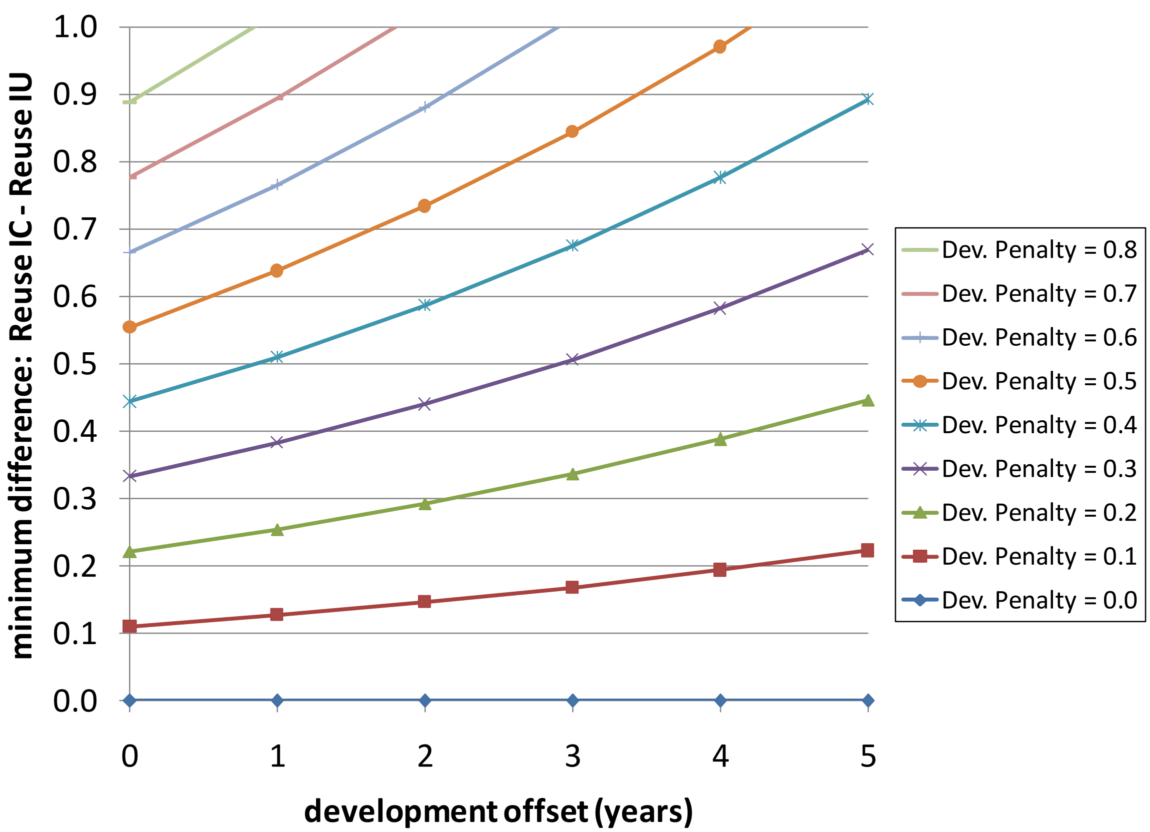

Figure 74: The tradeoff between development offset and reuse of Intended Common versus Intended Unique elements. If reuse is ignored (assumed to be zero), the vertical axis represents (1-Div). In order for a relative benefit to be maintained, increasing development penalties require a higher likelihood of reusing Intended Common components with respect to Intended Unique components. Points below each line are beneficial for the given development penalty, pen_{dev}.

6.1.3. Production Offsets

Three production cases are examined below: parallel, sequential overlapping, and sequential non-overlapping. The three cases are illustrated in Figure 75. A two product family is discussed for simplicity. The concepts extend to families of three or more products, albeit with increased complexity.

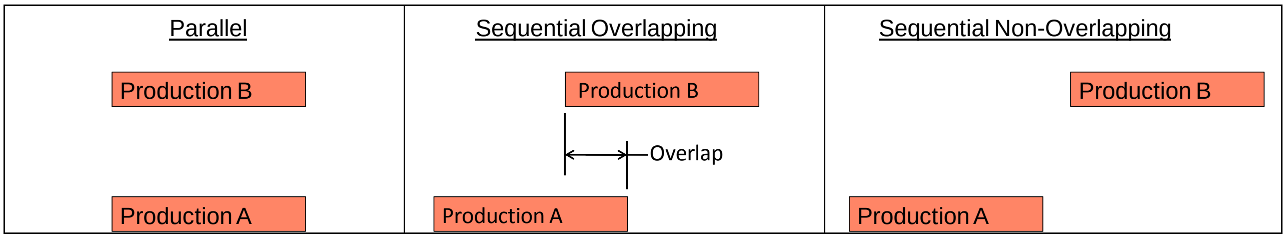

Figure 75: Three generic cases of production: parallel, sequential overlapping, and sequential non-overlapping.

The degree of overlap between Product A and Product B production influences the degree to which production benefits are realized and also the apportionment of these benefits between products. As is described later in this chapter, Parallel production provides the greatest variable cost benefit of commonality, while Sequential Non-Overlapping production provides the least. As is also shown later, the relative benefit of commonality shifts depending on the offset. Increasing offsets decrease the total benefit at the product family level and the remaining benefit becomes more heavily biased toward the follow-on variant.

The organization of this section is as follows. A simple production cost model is described. The model is then used to discuss the limiting cases of Parallel production and Sequential Non-Overlapping production, followed by a discussion of the more general case, that of Sequential Overlapping production.

The model is based on a simplified version of the factors identified during the literature review and the case studies and explicitly addresses the variable costs of production. Non-recurring costs associated with process development, tooling, new facilities, etc., are assumed to be included in the previously described development model. Further depth that allows for differentiation between additional aspects of development costs could be added in future work. Overhead costs are not explicitly addressed in the following production cost model, although overhead accounting that applies overhead based on a fixed percentage of a component's cost could be assumed to be implicitly included in the model. The most important limitation imposed by this exclusion is a lack of accounting for any potential differences in overhead that are associated with commonality. For example, an inventory benefit or penalty may result due to common component usage.[45] Incorporation of overhead is left to future work.

[45] A benefit results when the costs of capability are outweighed by a company's ability to reduce its inventory holdings due to common component usage. A penalty results when the costs of capability outweigh the part reduction benefit.

Total production costs for the product family are the product of each product's demand at each time period, $D_i(n)$, and product unit costs at each time period, $C_{unit\,,i}(n)$, summed over all time periods from 1 to N for all products from 1 to I. A discount rate, r, may be applied.

$$Cost_{PF\ Mfg} = \sum_{n=1}^{N} \sum_{i=1}^{I} \frac{D_i(n) * C_{unit\,,i}(n)}{(1+r)^n} \tag{6.18}$$

Unit costs are assumed to consist of materials and labor costs for the purposes of this discussion and model. Material costs are assumed to be determined by component capability and production rate, the factors cited most often during the case study interviews.[46] The capability of a component determines its baseline cost that is then discounted based on production rate (demand). Labor costs are assumed to be primarily influenced by learning curve effects. The importance of learning curves appears to have varied across the case studies. The military aircraft program was very aware of learning curve effects and always included these effects in determining unit cost. At the other end of the spectrum was the automotive case. Learning curve effects were not mentioned at all during this case study. The seeming lack of importance may be due to the well-established, high volume manufacturing systems within this industry. Labor tasks are well-understood and are likely to descend the learning curve very quickly given the high production volumes of this industry.[47] The combination of materials and labor costs (without applied overhead) is typically referred to as direct manufacturing costs.

For modeling purposes, each product's unit costs, $C_{unit\,,i}(n)$, consist of the summation of the relevant five component classes described in Chapter 2. In the two product example considered here, the costs are

$$C_{unit\,,A}(n) = \sum_{j=1}^{4} C_{class\ j}(n) \tag{6.19}$$

$$C_{unit\,,B}(n) = \sum_{j=3}^{5} C_{class\ j}(n) \tag{6.20}$$

The cost of each component class, j , is determined by Equation 6.21 which is based on the Theoretical First Unit cost, TFU_j, and may be increased by a capability penalty, pen_{cap}, and decreased by a discount factor, $d_{sl,j}(n)$, that is dependent on economies of scale, learning, and the relative proportion of a component's material costs to total first unit cost. Each term is described in more detail below and Table 11 provides a summary of the actual equations for each component classification.

$$C_{class\ j}(n) = TFU_j * \left(1 + pen_{cap}\right) * d_{sl,j}(n) \tag{6.21}$$

TFU costs represent the product of a cost basis associated with each of the five component categories and a ratio, r_{mfg}, that allows for relative scaling between product development

[46] The case study companies were keenly aware of the influence of negotiations on material costs but also recognized capability and rate as "fundamental" factors that influence these costs. An attempt to model negotiation was beyond the scope of this research.

[47] This is likely an example of process commonality, although the topic of learning curves was not investigated within the automotive case.

costs and manufacturing unit costs. Refer to Table 11 for TFU values for each of the five component classes.

A capability penalty, pen_{cap}, is assumed to be incurred by any component that was developed *with the intent* of becoming common; i.e., for Class 2 and Class 4 components. Barring the two products sharing the exact same set of requirements for an Intended Common component, the component will have a penalty from the perspective of at least one of the products. The capability penalty is determined in design and is incurred regardless of whether or not the design is actually used by more than one product. In the context of the sequentially developed two-product example, the penalty is designed into Intended Common elements during Product A's development phase. The Intended Common parts become "Common" or "Unique to A" once Product B has been developed. An Intended Common component that becomes unique to Product A incurs a manufacturing cost penalty without the potential offsetting benefits of scale and learning.

The case study companies were well aware of the potential for a capability penalty. The case studies also indicated that the capability penalty is likely to be applied to both products in varying degrees rather than to one product. This outcome is due to the fact that the component requirements for one product do not always represent the superset of requirements for the second product. Given this outcome, a capability penalty is incurred by all products, but to varying degrees. In the simple model, the capability penalty is assumed to be equal for all variants. Differentiation by product is left to future work. Refer to Table 11 for the capability penalties that are assigned to each of the five component classes.

The last term in Equation 6.21, $d_{sl,j}(n)$, represents the manufacturing discount due to scale and learning. This discount increases in the case of common production. Economies of scale are applied to materials costs and are associated with a supplier's typical willingness to provide a manufacturer with cost reductions based on increasing purchase rates. Learning curve benefits are based on the total cumulative production of the component. In the case of common components, cumulative production eventually exceeds the total of any one product. Learning curve benefits are assumed to apply to the labor portion of a component's cost. The relative portion of TFU costs associated with material cost is defined by r_{mat}. The discount term is expressed as

$$d_{sl,j}(n) = r_{mat} * f_{scale}\left(rate_j\left(D_j(n)\right)\right) + (1 - r_{mat}) * f_{learning}\left(cum\_prod_j\left(\sum_{m=1}^{n-1} D_j(m)\right)\right) \tag{6.22}$$

The demand curves for common and unique components determine the rate, $D_j(n)$, and cumulative production, $\sum_{m=1}^{n-1} D_j(m)$, inputs for Equation 6.22. Rates are either the per period demand for Product A, the per period demand for Product B, or the combined per period demand for Product A and Product B. The demands are linked to each of the five TFU classes, j, as specified in the rightmost column of Table 11. Note that the demand rate for a common component is not necessarily greater than the individual demand rates, given a time period that does not have overlapping production. The implications of this outcome are discussed in later sections. Cumulative production represents the total production up to and including the production at the prior time period, $n-1$. As in the case of demand rates, cumulative production can be based on the demand histories of the individual products or on the combined demand history of the two products.

The following shorthand notation is utilized to describe $d_{sl,j}$, for the three demand scenarios. These discounts are assumed to be calculated for the time period, n, of interest.

- $d_{sl}(A)$: Discount due to production based on Product A demand
- $d_{sl}(B)$: Discount due to production based on Product B demand
- $d_{sl}(A+B)$: Discount due to production based on Product A and Product B demands

Table 11: Factors influencing the costs of each component class as described by Equation 6.21.

Class	**Class Description (symbolic)**	**Theoretical First Unit Cost (independent baseline)**	**Capability Penalty (pen_{cap})**	**Discount (d_{sl}) depends on**
1	$IU_A \rightarrow U_A$	$r_{mfg} * (1-COMM) * C_{dev,ind,A} * (1-Reuse_{IU})$	0	D_A
2	$IC \rightarrow U_A$	$r_{mfg} * COMM * C_{dev,ind,A} * Div$	pen_{cap}	D_A
3	$IU_A \rightarrow C$	$r_{mfg} * (1-COMM) * C_{dev,ind,A} * Reuse_{IU}$	0	$D_A + D_B$
4	$IC \rightarrow C$	$r_{mfg} * COMM * C_{dev,ind,A} * (1-Div)$	pen_{cap}	$D_A + D_B$
5	U_B	$r_{mfg} * [C_{dev,ind,B} - COMM * C_{dev,ind,A} * (1-Div) - (1-COMM) * C_{dev,ind,A} * Reuse_{IU}]$	0	D_B

The manufacturing benefit of producing common components in relation to producing independently designed alternatives can be computed for each of the five component classes, as described by the equations in Table 12. A production cost benefit results when the product of the capability penalty and scale and learning discount are less than 1. Intended Unique components that remain unique (Classes 1 and 5) are not impacted by commonality. Intended Common components that actually become unique (Class 2) create a unit cost manufacturing penalty due to the cost of increased capability (related to the pen_{cap} multiplier). Intended Common components that become common (Class 4) create a tradeoff between the costs of capability and the increased benefits of shared scale and learning. Intended Unique components that become common (Class 3) are not subject to the capability penalties associated with common design intent. This class of components always has an associated benefit, assuming selected components are well-matched to the needs of the follow-on product.[48] The reader is reminded that this last category of components appears to be the

[48] A reasonable argument can be made for the incurrence of a capability penalty when reusing Intended Unique elements. This penalty would be applied to the follow-on product only, given that the component was originally

most common form of reuse, based on the case studies. The benefit equations help to illustrate why this approach to commonality may be favorable in relation to the alternative of producing Intended Common elements.

Table 12: Unit production cost differential for the five component classifications (undiscounted). Intended common components result in either a production penalty (Class 2) or a trade (Class 4) in relation to the independent alternative. Reuse of Intended Unique components (Class 3) results in a production benefit. Classes 1 and 5 are unaffected by commonality.

Class	Class Description (symbolic)	Common Production Cost Minus Independent Production Cost by Component Class (unit cost TFU multiplier, undiscounted)	Production Cost Benefit or Penalty?
1	$IU_A \rightarrow U_A$	0	Baseline
2	$IC \rightarrow U_A$	$TFU_2 * pen_{cap} * d_{sl}(A)$	Penalty
3	$IU_A \rightarrow C$	$TFU_3 * [d_{sl}(A+B) - d_{sl}(A) - d_{sl}(B)]$	Benefit
4	$IC \rightarrow C$	$TFU_4 * \left[\left(1 + pen_{cap}\right) * d_{sl}(A+B) - d_{sl}(A) - d_{sl}(B)\right]$	Trade
5	U_B	0	Baseline

Important from the product development perspective is the decision to develop Intended Common or Intended Unique components. By inspection of Table 12, components that are Intended Unique to Product A (Classes 1 and 3) always provide a production cost benefit assuming that some degree of reuse occurs (i.e., that TFU_3 is non-zero) and that benefits of increasing scale and learning exist. Intended Common components produce a production cost benefit when the following condition is met (lead terms indicate benefit magnitude):

$$r_{mfg} * COMM * C_{dev,ind,A} * pen_{cap}\left[Div * d_{sl}(A) + (1 - Div)[d_{sl}(A+B) - d_{sl}(A) - d_{sl}(B)]\right] < 0 \tag{6.23}$$

For the above condition to be met, the penalty of excess capability must be outweighed by the increased discount associated with higher production rates and cumulative production histories of common components. The general relationship is illustrated in Figure 76. The loss of commonality often appears to be ignored in industry and by researchers, meaning that divergence is assumed to be zero. The production penalty associated with this lost commonality is also ignored, producing an overly optimistic estimate of the benefits of pursuing Intended Common elements.

developed for a unique application. The assumption here is that Intended Unique components are selected for reuse only when the capability penalty is negligible.

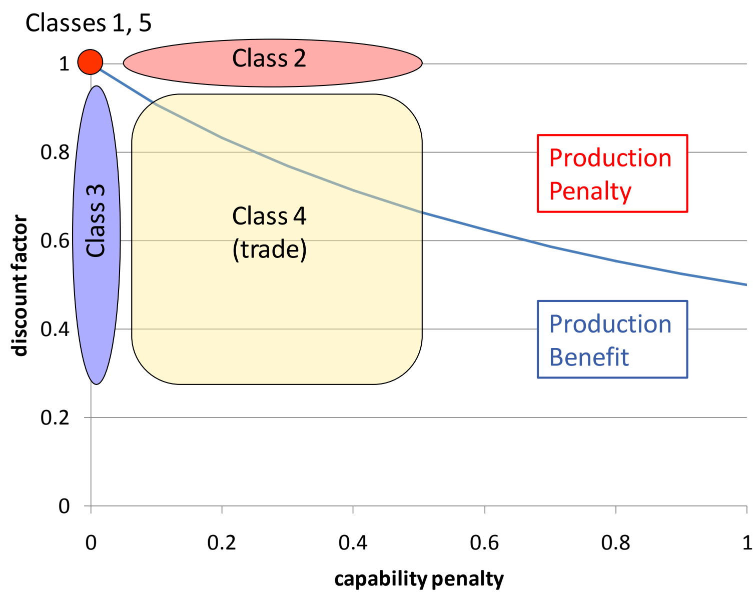

Figure 76: A notional view of the production cost tradeoff between capability penalty and discounting due to economies of scale and learning. Lower manufacturing discount factors and lower capability penalties produce a net cost reduction. The graphics illustrating the classes are illustrative and are not supported by data.

For the purposes of comparison to development costs, a normalized discount referred to as, $\tilde{d}_{SL}$ is computed for each of the three demand scenarios. This term combines demand histories, materials fractions, and economic discounting to produce a unit cost multiplier for a given set of inputs. The discounts are utilized to calculate total production costs for Product A (Equation 6.24) and Product B (Equation 6.25). Product family production costs are the summation of the two equations.

$$C_{prod,A,total} = \Big[\big[(1-COMM)(1-Reuse_{IU}) + COMM * Div * pen_{cap}\big] * \tilde{d}_{SL}(A) + \big[(1-COMM) * Reuse_{IU} + COMM * (1-Div) * pen_{cap}\big] * \tilde{d}_{SL}(AB)\Big] * r_{mfg} * C_{dev,ind,A} * \sum_{n=1}^{N} D_A(n) \quad (6.24)$$

$$C_{prod,B,total} = \Big[\big[C_{dev,ind,B} - COMM * C_{dev,ind,A} * (1-Div) - (1-COMM) * C_{dev,ind,A} * Reuse_{IU}\big] * \tilde{d}_{SL}(B) + C_{dev,ind,A}\big[(1-COMM) * Reuse_{IU} + COMM * (1-Div) * pen_{cap}\big] * \tilde{d}_{SL}(AB)\Big] * r_{mfg} * \sum_{n=1}^{N} D_B(n) \quad (6.25)$$

The following sections provide a discussion of the spectrum of production types. The ends of the spectrum, parallel and sequential non-overlapping production are discussed first, followed by the more general case of sequential overlapping production. The discussion is in the context of the simple production model described above, applied to a hypothetical two-product family. Each section examines the potential cost implications of commonality on the five component classes, followed by application to a two product example which is a simple combination of the relevant component classes for each of the two products. The implications of each mode of production are discussed at the end of their relevant section.

Unless noted otherwise, the following assumptions are made about the two product family:

- Product A and Product B are each produced at the rate of $D(n)$= constant = 100 units/year for a period of 5 years. Production of the two products may have an offset, as indicated in the examples.
- Intended commonality, $COMM$, is 50%.
- Divergence is defined by the following equation:

$$Div = 1 - \frac{1}{(1+0.2)^s}$$

- Reuse is defined by the following equation

$$Reuse_{IU} = \frac{0.2}{(1+0.05)^s}$$

- Economies of scale are defined as

$$scale = 0.7 * e^{-2*D(n)/D} + 0.3$$

  Where D= 100
- Learning is based on an 85% learning curve. Refer to Chapter 2 for details.
- Sixty percent of the TFU costs are assumed to be materials (r_{mat} =0.6). While this is likely low for a systems integrator, the lower level has been selected in order to account for the learning curve benefits that are internalized in material costs. (Supplier labor is a portion of purchased material costs.)
- Unless otherwise noted, a capability penalty, pen_{cap}, of 10% is assumed.
- When noted, an economic discount rate, r, of 15% is applied.

Parallel Production Example

When products are produced in parallel (offset equals zero), common components are procured and integrated at the aggregate demand levels of all products that share these components. In the case of a two product family, a common component is utilized at the combined production rates of both Product A and Product B, while a unique component is utilized at the production rate of either Product A or Product B. The demand profiles illustrated in Figure 77 show the difference between demand for a common component ("combined demand") and demand for a unique component ("Demand A" or "Demand B") and are based on the previously described example parameters.

The numerical example production costs are illustrated in Figure 78 and Figure 79 for the case of parallel production. Figure 78 shows the unit production costs for the five component classes. This figure can be interpreted as the cost of a component (or equivalent group of components), for a given component classification. Class 2 components (IC→ U_A) are the most costly as they incur a capability penalty but are procured at Product A rates. Class 3 components (IU_A →C) are the least expensive as they have no capability penalty and are procured at the combined production rate. Class 4 components (IC→C) are more expensive than the Class 3 components yet less expensive than the independent components (Classes 1 and 5). Figure 79 illustrates overall product manufacturing costs based on the relative portions of component classes contained in each design, for the specific set of example parameters defined above. These relative proportions are determined by the initial plan for commonality

($COMM$) and by the divergence and reuse factors. Figure 79 indicates that, in this example, both products realize a production cost benefit from the use of common components in comparison to the alternative of independent development with reuse of Intended Unique components.

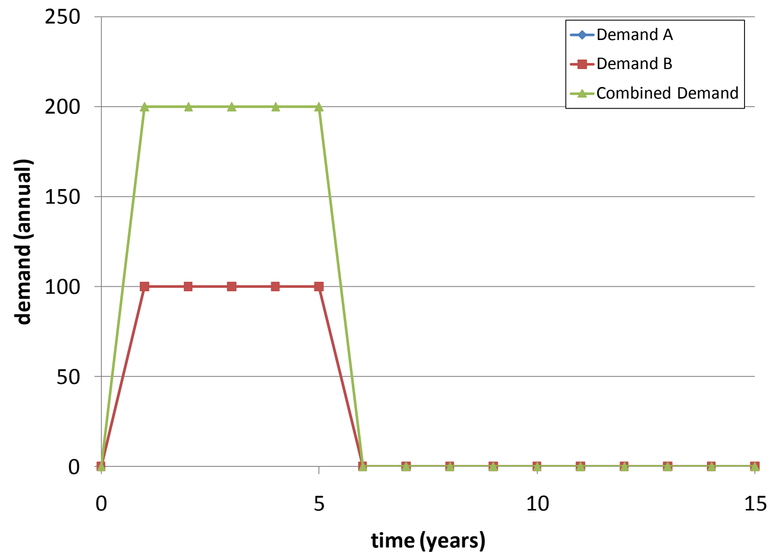

Figure 77: Parallel Production: Demand for the numerical example (offset = 0). In this case, demand for products A and B is 100 units per year for Year 1 through Year 5. Combined demand is 200 units per year for the same period. Common components are procured at the combined rate, while Unique components are procured at the rates for either Product A or Product B. In this example, the demand profiles for Product A and Product B are completely overlapping. ("Demand B" is visible.)

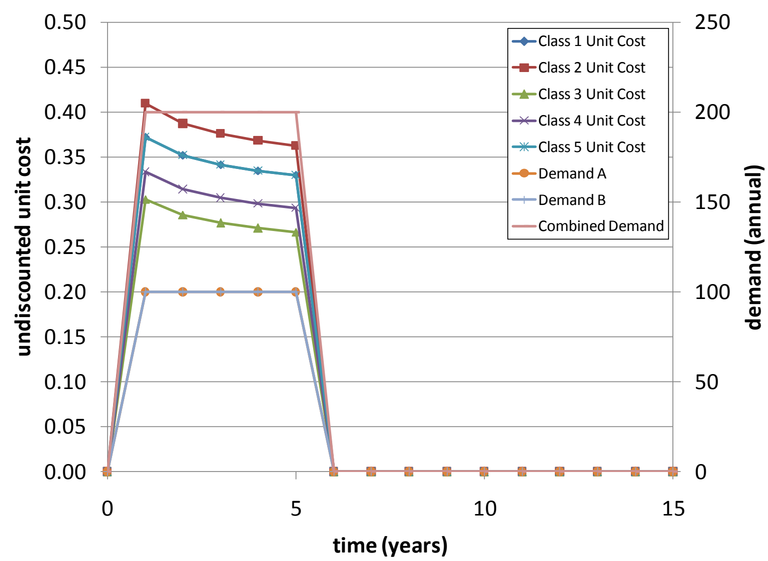

Figure 78: Parallel Production: Unit costs (undiscounted) for the five component classes and demands for Product A, Product B, and Combined. Classes 1 through 4 represent those components associated with Product A. Classes 3 through 5 represent those classes associated with Product B. Classes 1 and 5 have equivalent unit costs in this example.

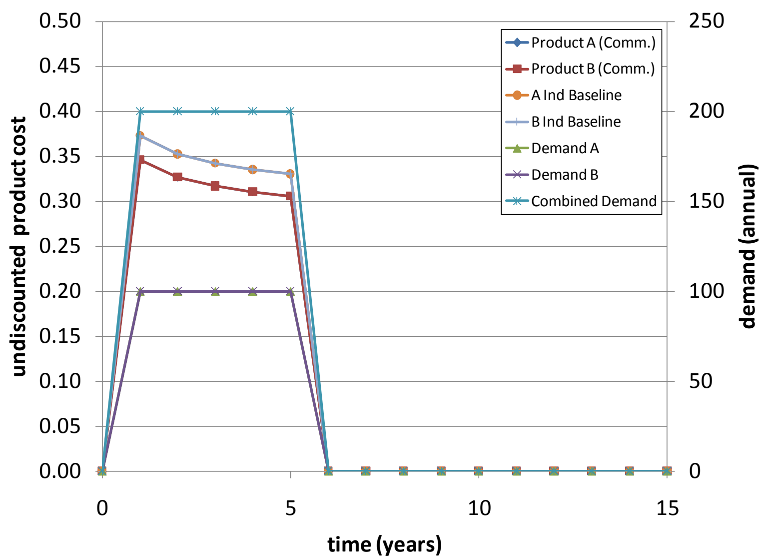

Figure 79: Parallel Production: Product A and B costs (undiscounted) are equivalent in this example. Both products benefit equally from scale and learning. Both realize additional scale and learning benefits in relation to their baselines of independent development with reuse (red squares vs. orange circles in the above figure. Indicated costs represent the cost of producing a single unit of either Product A or Product B, at the given time.

Parallel production serves as a useful baseline for comparison to sequential production. As illustrated in later comparisons between parallel production and sequential production, the assumption of parallel production provides the most optimistic estimates of the benefits of commonality. Parallel production maximizes shared economies of scale on common parts through maximizing the overlap between production of the two products. Multi-product benefits of scale and learning are recognized immediately and are shared equally between both products. For the specific parameters of the example, Table 13 summarizes the normalized costs of production for the two products and the product family as a whole. Both products realize a total production cost benefit, even in the presence of a 10% capability penalty (pen_{cap}) on Intended Common parts. Table 14 provides costs that are adjusted for a 15% discount rate. The relative benefits of commonality remain unchanged although total costs are reduced by the discount rate. Truly parallel production was not observed in the case studies, although significant degrees of overlap certainly were.

Table 13: Normalized total production costs (undiscounted) for the parallel production example, with and without a capability penalty (pen_{cap}) of 10%. In parallel production, both products realize the same benefit from commonality. In this example, the net production cost reduction is approximately 10%. A manufacturing benefit may exist even in the presence of a capability penalty (rightmost column), as long as the cost of a capability penalty is outweighed by economy of scale and learning curve benefits.

	Independent (offset = 0)	Parallel (offset = 0, no cap. penalty)	Parallel (offset = 0, 10% cap. penalty)
A Production Cost	0.50	0.45	0.47
B Production Cost	0.50	0.45	0.47
Total Production Cost	1.00	0.89	0.93

Table 14: Normalized total production costs given a 15% discount rate. Discounting reduces total costs but does not change the relative benefit of commonality. Normalization is based on the undiscounted, total production cost of the independent product designs.

	Independent (offset = 0)	Parallel (offset = 0, no cap. penalty)	Parallel (offset = 0, 10% cap. penalty)
A Production Cost	0.34	0.30	0.32
B Production Cost	0.34	0.30	0.32
Total Production Cost	0.68	0.60	0.63

Sequential Non-Overlapping Production Example

Non-overlapping production (offset > Product A production duration) completely eliminates shared economies of scale and alters the assignment of learning curve benefits to each product. Economies of scale benefits beyond those associated with an individual product are non-existent due to the lack of production overlap between products. Additional learning curve benefits do exist but their apportionment is not shared equally between the two products as was the case in parallel production. As a result of the purely sequential nature of non-overlapping production, the lead variant does not realize an additional learning benefit beyond that associated with the lead variant's own production history. Any capability penalty associated with Intended Common components is not offset by shared economies of scale and learning, from the perspective of Product A. The result: lead variant production costs increase in comparison to the parallel production case and are higher than the independent alternative given a non-zero capability penalty. The second variant, Product B, realizes learning curve benefits based on Product A's prior production history. Product B's costs also increase with respect to the parallel case since shared economies of scale do not exist. The case of sequential non-overlapping production represents the minimal potential production benefits of common components.

The numerical example was examined for the case of sequential non-overlapping production. Figure 80 illustrates the demand history for both products. The purely sequential nature of production means that demand for a common element never exceeds the demand of an individual product, which is 100 units per year in this example. Figure 81 provides the unit cost histories for each of the five component classes that are combined to produce Product A and Product B costs. The components that actually become common (Classes 3 and 4) continue to descend the learning curve as they shift from being utilized in Product A to being utilized in Product B. The capability penalty (10% in this example) makes commonality undesirable from the standpoint of both products when compared to the independent alternatives. Especially note that Class 5 (Product B Unique) component costs quickly reach a cost that is below Class 4 (IC→C) due to the capability penalty placed on the common components. Class 3 components (IU_A →C) provide a compelling production cost benefit. An examination of cost at the product level (Figure 82) indicates that a net production penalty is associated with production of Product A. Product B realizes a small unit cost benefit that starts at 3.5% below the independent alternative and decreases to 1.2%. The production cost totals for Product A, Product B and the product family are reported in Table 15 (undiscounted) and Table 16 (discounted).

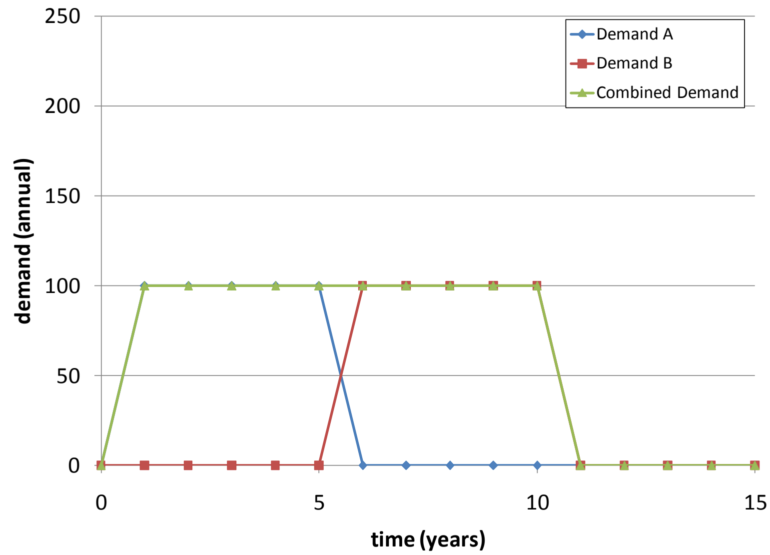

Figure 80: Sequential Non-Overlapping Production: Demand for the numerical example (offset = 5 years). The combined demand for common elements is 100 units/year, the same as the demand for an individual product. For common components, learning benefits accrue beyond those associated with an individual product. Shared economies of scale are non-existent. Refer to next figure.

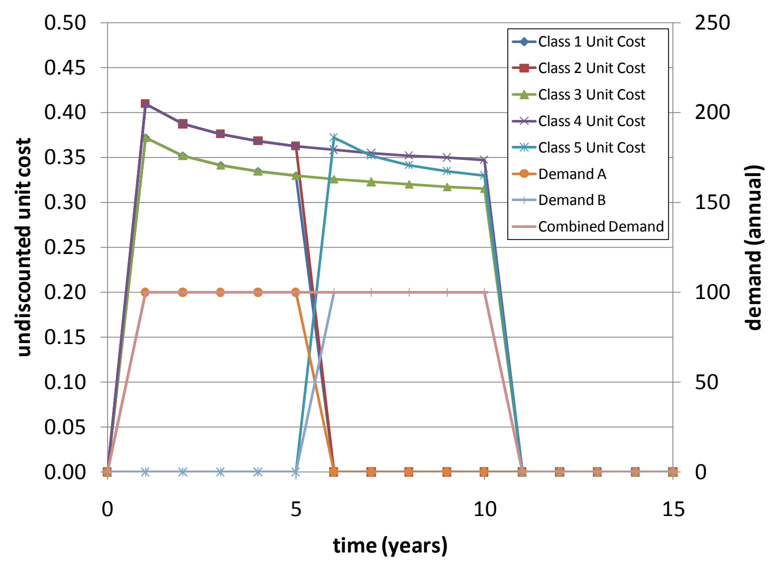

Figure 81: Sequential Non-Overlapping Production: Unit costs (undiscounted) for the five component classes and demands for Product A, Product B, and Combined (five year offset). In this numerical example, the only benefit of commonality in relation to independent designs results from reusing Intended Unique components in Product B (Class 3). All other outcomes result in production penalties, with the exception of a one period benefit of Class 4 components with respect to Product B Unique (Class 5) components. Note that Class 2 unit costs match those of Class 4 during production of Product A. Classes 1 and 3 unit costs also match during the same period.

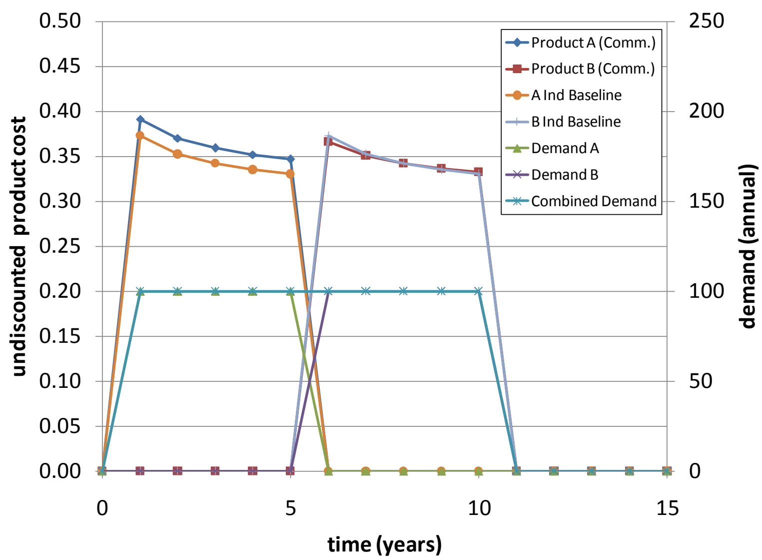

Figure 82: Sequential Non-Overlapping Production: Product costs (undiscounted) and demands given Sequential Non-Overlapping production (five year offset). In this example, significant penalties are realized in the production of Product A. Product B realizes a small benefit, a 3.5% unit cost reduction at most. Given the parameters of this example, divergence has resulted in 20% commonality (TFU) from Intended Common components (Class 4), down from the intent of 50%. Product B Intended Unique components (Class 5) are 72% of Product B TFU costs as a result. These values influence the total product costs reported above.

Table 15: Undiscounted production costs for Product A, Product B, and the product family. Without a capability penalty, a slight cost reduction for each product is achieved due to multi-product learning benefits. The addition of a capability penalty (10%) results in a net production cost increase for Product A and for the product family as a whole. Also note that the un-penalized costs of common production have risen considerably with respect to the baseline of parallel development. (Refer to Table 13.)

	Independent (offset = 5)	Sequential Non-Overlapping (offset = 5, no cap. penalty)	Sequential Non-Overlapping (offset = 5, 10% cap. penalty)
A Production Cost	0.50	0.49	0.53
B Production Cost	0.50	0.49	0.50
Total Production Cost	1.00	0.99	1.03

Table 16: Discounted (r = 15%) production costs. Costs change but the trends are still the same as in the undiscounted case.

	Independent (offset = 5)	Sequential Non-Overlapping (offset = 5, no cap. penalty)	Sequential Non-Overlapping (offset = 5, 10% cap. penalty)
A Production Cost	0.34	0.34	0.36
B Production Cost	0.17	0.16	0.17
Total Production Cost	0.51	0.50	0.52

The above example does not provide a compelling case for sequential non-overlapping production benefits; however, alternative outcomes may arise. For example, if the benefits of learning are increased, Product B may realize more significant production cost benefits. These discounted benefits must then be traded against the penalties incurred during Product A production. The uncertainty of future benefits of commonality combined with the more certain Product A production cost penalties do not make a compelling case for the proactive development of Intended Common elements in sequential, non-overlapping settings. That said, it is important to reiterate that production costs are only one component of lifecycle profitability.

Sequential Overlapping Production

Sequential Overlapping production (0 < offset < Product A production duration) spans between the Parallel and Sequential Non-Overlapping modes of production. In sequential overlapping production, partial offsets between two production phases create pre-overlap, overlap, and post-overlap regions (Figure 83), each of which impact the benefits and penalties of commonality from a production standpoint. The lead variant (Product A) initially enters production without shared economies of scale and learning curve benefits. In this pre-overlap phase, Product A incurs capability-driven production cost penalties on Intended Common elements, as was the case in sequential non-overlapping production. Once Product B enters production (the “overlap” phase), shared economies of scale and accelerated learning curve benefits result from the combined demands of Product A and Product B. During this period, production cost trends are similar to the parallel production scenario described above. The post-overlap phase of production starts when Product A is no longer produced. At that time, shared economies of scale benefits are lost. Cumulative learning curve benefits remain and continue to accrue to the benefit of Product B, but do so at a slower rate due to the reduced demand for common components that is associated with production of Product B only.

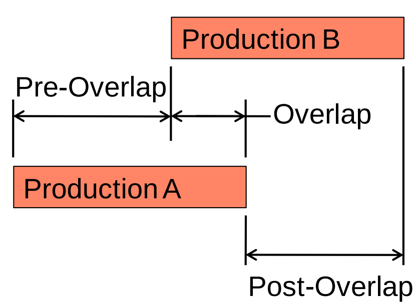

Figure 83: Offsets in production create pre-overlap, overlap, and post-overlap phases. The pre-overlap phase length is equivalent to the production offset.

As an example of offset production, the previous numerical example was modified to have a production offset of 2 years (40% of the individual product production duration). (Refer to Figure 84.) During the pre-overlap period, component costs follow the same trends as illustrated in the sequential non-overlapping case. Production rates for common elements are doubled during the overlap period and result in shared economies of scale and accelerated learning. Combined production of Product A and Product B results in an immediate unit cost reduction for Product A as illustrated in the Class 3 and Class 4 component cost dips of Figure 85. When Product A production ends, the shared economy of scale benefit is lost and the cost of a common component increases. In this example, common components that carry a capability penalty (Class 4) cost more than the independent alternative during the post-overlap phase, although higher rates of learning could reverse this trend. Figure 86 provides product level costs. Product A costs exceed the costs of the independent alternative until Product B production starts in Year 3. Product B costs are lower than the independent alternative until Product A production ends. Given the parameters of the numerical example, economies of scale have a larger influence on relative costs than learning curve benefits and these benefits of scale are reversible. In the sequential overlapping production example presented here, Product A breaks even with the independent alternative (assuming a 10% capability penalty) while Product B realizes a slight total production cost reduction (4%). (Refer to Table 17 and Table 18.) The production benefit is improved over the sequential overlapping case although the benefit is relatively small, given the parameters of this specific example.

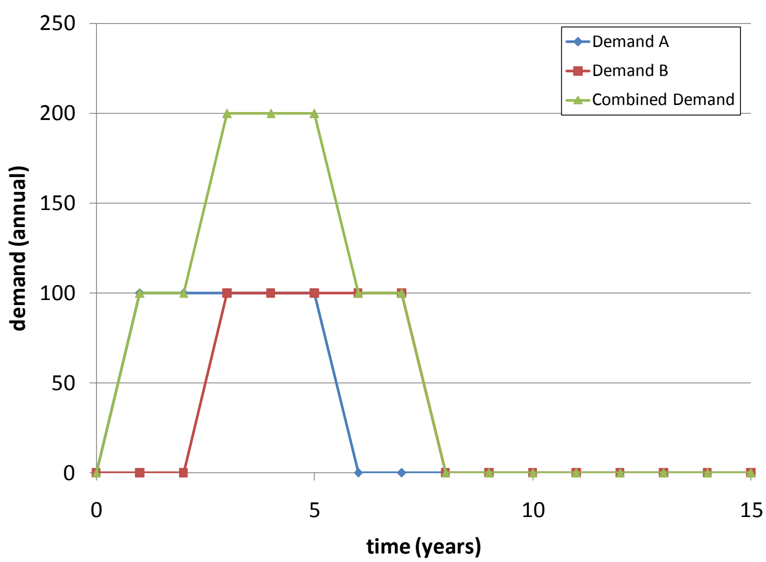

Figure 84: Sequential Overlapping Production: Demand profiles for Product A, Product B, and Combined given a two year offset. During the overlap period (years 3 through 5 in this example), combined demand is greater than that of any one product. Shared economies of scale and accelerated learning benefits apply to common components during this period of overlap.

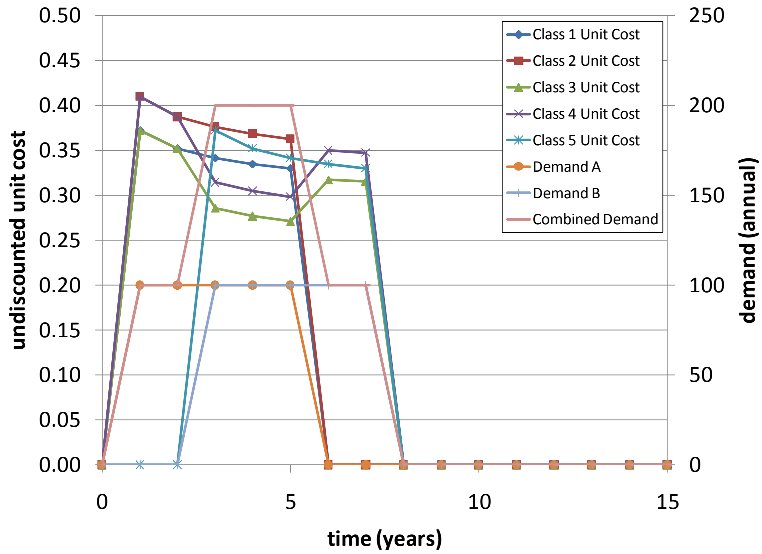

Figure 85: Sequential Overlapping Production: Unit costs (undiscounted) for the five component classes and demands for Product A, Product B, and Combined (two year offset). The common component (Classes 3 and 4) cost reduction during Year's 3 through 5 is primarily the result of shared economies of scale, but also includes accelerated learning.

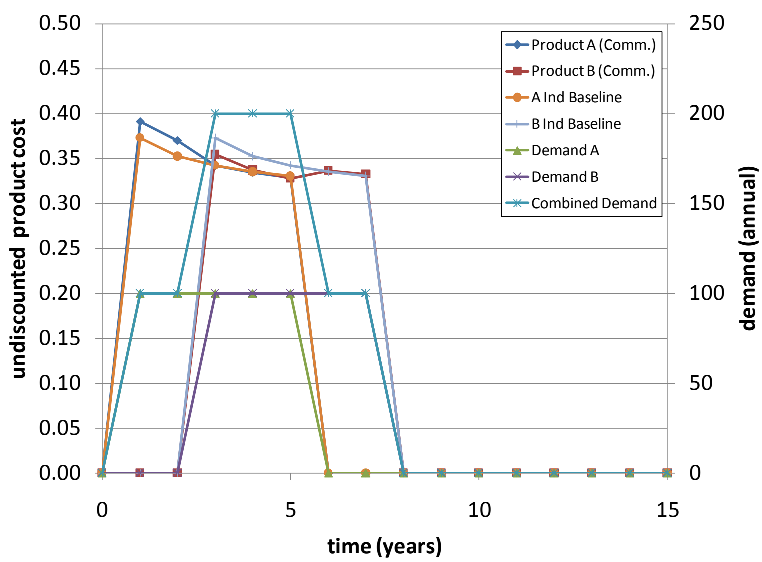

Figure 86: Sequential Overlapping Production: Product costs (undiscounted) for the numerical example and demand profiles (two year offset). Product A costs are elevated with respect to the independent alternative until production of Product B begins in Year 3. Likewise, Product B costs are lower than the independent alternative until Product A production ends in Year 5. Class 4 components are 35% of total TFU costs (compared with the intent of 50%) and Class 5 components are 56%.

Table 17: Undiscounted production costs for Product A, Product B, and the product family in the case of Sequential Overlapping production. In this example, Sequential Overlapping production (without penalty) provides production cost benefits to each of the individual products and to the product family. Application of the 10% capability penalty results in no commonality benefit from the Product A perspective and a reduced benefit to Product B. The remaining product family benefit (2%) is small on a percentage basis.

	Independent (offset = 2)	Sequential Overlapping (offset = 2, no cap. penalty)	Sequential Overlapping (offset = 2, 10% cap. penalty)
A Production Cost	0.50	0.48	0.50
B Production Cost	0.50	0.47	0.48
Total Production Cost	1.00	0.95	0.98

Table 18: Discounted (r = 15%) production costs for the sequential overlapping version of the numerical example. Costs change but the trends are still the same as in the undiscounted case.

	Independent (offset = 2)	Sequential Overlapping (offset = 2, no cap. penalty)	Sequential Overlapping (offset = 2, 10% cap. penalty)
A Production Cost	0.34	0.33	0.34
B Production Cost	0.26	0.24	0.25
Total Production Cost	0.60	0.56	0.59

The case of overlapping production spans between completely parallel and sequential, non-overlapping modes of production. A range of offsets was explored to better understand the impact of production offsets on the production benefits/penalties of commonality for the specific parameters of the production example. Figure 87 contains undiscounted and discounted comparisons of total production costs for Product A, Product B, and their sum. For this example, parallel production (offset = 0) results in a net production cost benefit. As the offset increases, the overlap period reduces, the economies of scale benefit decreases, and the production benefit of commonality eventually becomes a penalty. For this specific example, the crossover occurs at approximately 3 years for the undiscounted case. Offsets that are less than the crossover point provide production cost benefits while offsets greater than the crossover point create penalties, all other parameters being equal. At offsets greater than or equal to five years (i.e., the sequential non-overlapping domain), the benefits of producing a common element are limited to accrued learning curve benefits. As the offset increases beyond a value of one, no additional benefit is realized. An argument could be made that offsets greater than one produce a loss of learning that increases with the time that a common component is not in production. The model does not include this feature, although it could be added in future work. It is also important to note that Product B always has costs that are less than or equal to those of Product A. Costs are equal given parallel production (offset = 0). As soon as an offset is introduced, Product B leverages the learning benefits of the Product A production that accrued prior to the start of Product B production.

A range of divergence values was also examined for the numerical example parameters, using a two year offset (Figure 88). For this example, the loss of 70% or less of the intended commonality results in a net production cost benefit in comparison to the independent alternative. The maximum benefit is a 3% total production cost reduction. The maximum penalty is a 1% increase in total production costs if all commonality is lost. While these percentages may translate into large cost differences in the context of complex product families, the differences are clearly incremental rather than major percentage shifts.

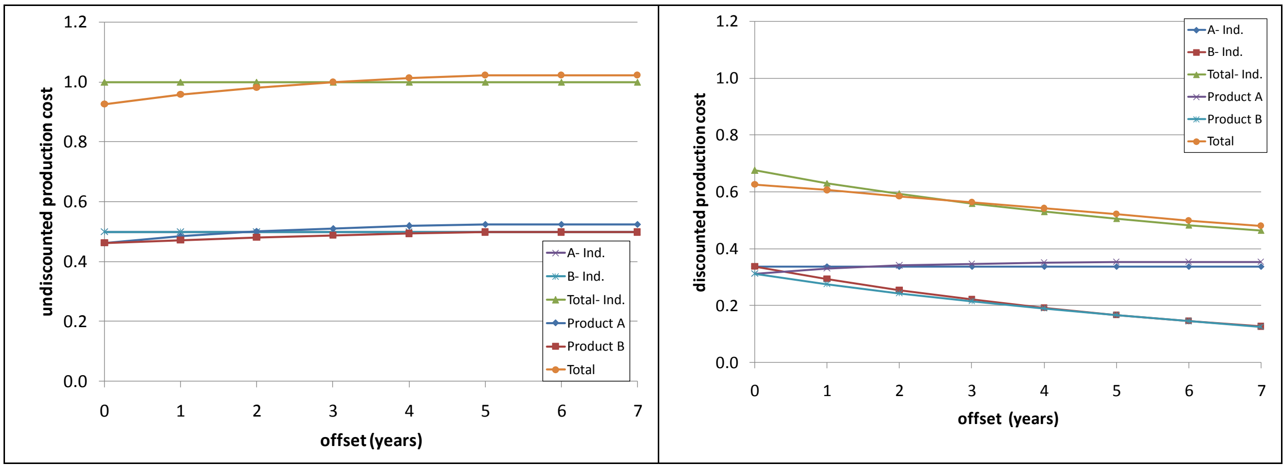

Figure 87: The impact of production offset on the production costs of the common and independent product alternatives of the numerical example. Undiscounted costs (left) and discounted costs (right, r = 15%). In this example, commonality produces the largest cost benefit at a zero offset (parallel production). Commonality produces a penalty for offsets greater than 3 years in the undiscounted case and greater than approximately 2 ½ years in the discounted case. Discounting decreases the relative importance of later production benefits.

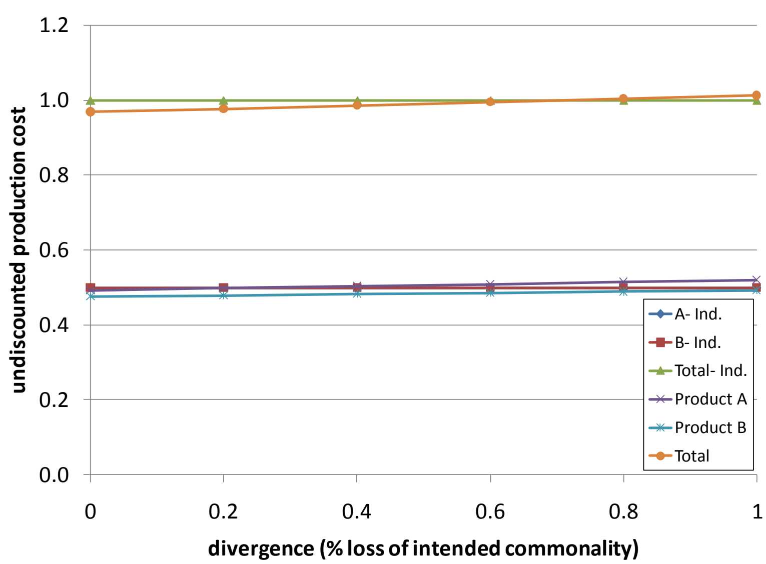

Figure 88: Product A, Product B, and Total production costs for divergence levels ranging from 0 (no loss of intended commonality) to one (complete loss of intended commonality). For this specific example, commonality produces a net production benefit when less than 70% of the Intended Common components become unique components. A 15% discount rate lowers the crossover to 60%. (Assumption: 2 year offset.)

The combination of divergence and offset is illustrated in the figures below. Divergence is assumed to be time dependent in the model and is therefore related to offset. (Refer to the production model assumptions of this chapter and to Chapter 5, Equation 5.1.) Offset however, influences other factors such as the degree of shared economies of scale and the apportionment of learning benefits between products. Low degrees of divergence and small offsets produce the greatest benefits in the context of the model presented here. Figure 89 is a contour plot of the Product A production cost benefit (or penalty) of commonality with respect to the alternative of producing independent products. The red line indicates the crossover between commonality providing a benefit to Product A versus a penalty. Figure 90 illustrates the Product B view. Product B realizes a net production benefit for all cases except those of large (5 year) offsets and low divergence. The result of Figure 90 is somewhat counterintuitive, as low divergence may be perceived as being beneficial for a given offset value. The five year offset marks the complete elimination of shared economies of scale benefits, yet the capability penalty for common components remains in the product designs. In the case of non-overlapping production, Product B production is less costly if commonality declines. Doing so replaces production of overly capable components with those that are less costly, for a given production rate.[49] Figure 91 provides the combined Product A and B view.

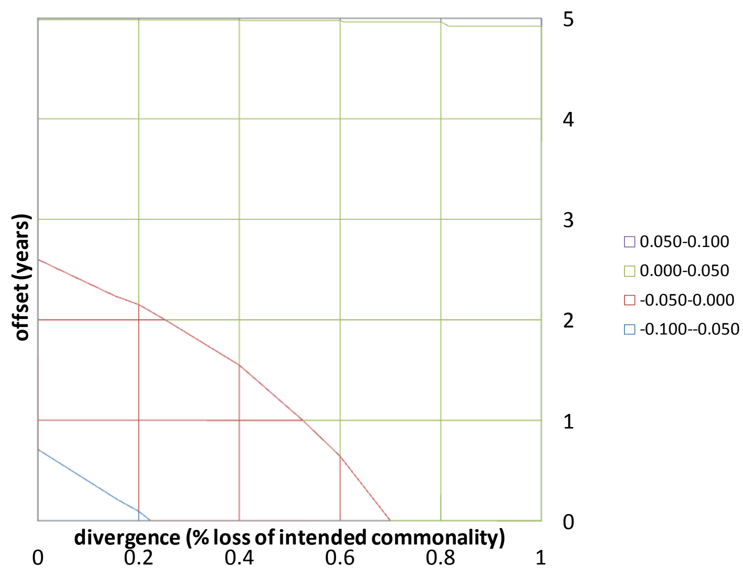

Figure 89: Product A production cost benefit for a range of divergence values and offsets. The lower left corner represents the greatest benefit. A benefit is realized for values that lie below the red contour line.

[49] The degree of learning also influences this outcome, although in this example, economies of scale and capability penalties are the dominant differentiators between the common and independent alternatives.

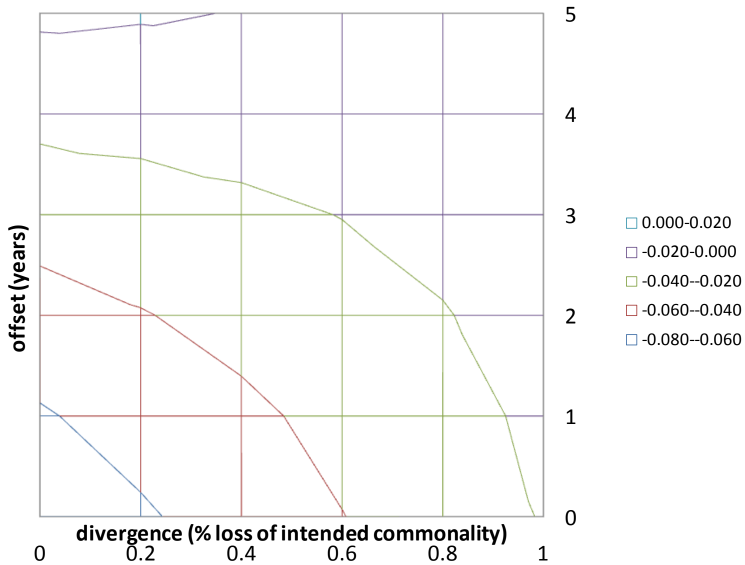

Figure 90: Product B production cost benefit for a range of divergence values and offsets. Commonality produces a net benefit for all values except those in the far upper left corner (high offsets and low divergence).

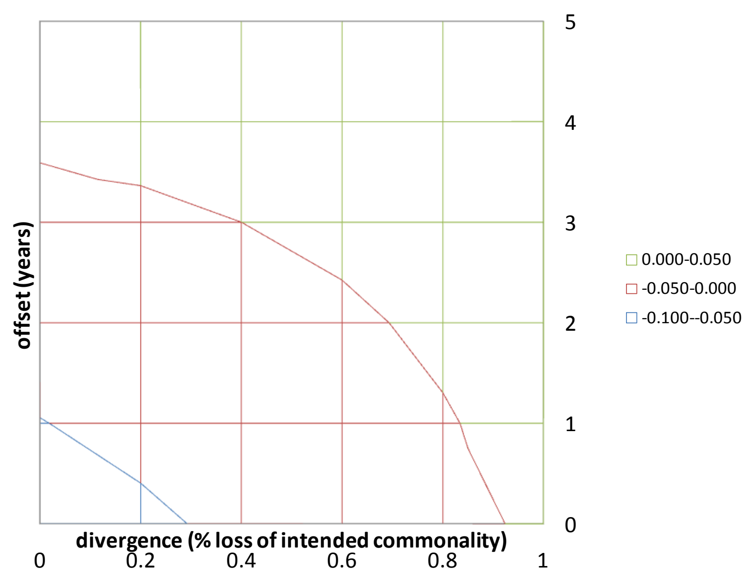

Figure 91: Product family production cost benefit for a range of divergence values and offsets. A net production cost benefit is realized for divergence and offset combinations that lie below the red contour line.

Until this point, production rates have been assumed to be equal between Products A and B. The case studies indicated that production rates vary considerably between the members of a product family. A factor of two was not uncommon in the case studies. Relative volumes were examined for the example parameters and the specific cases of parallel production (Figure 92) and sequential production with a two year offset (Figure 93). In the case of parallel production, low Product B production rates produce a strong incentive for Product B to use the Intended Common elements developed by Product A (18% Product B unit cost reduction for a production rate of 50 units/year). Product A also benefits, although to a lesser extent (4% reduction). As the Product B production rate increases, the cost benefit to Product B decreases and becomes a penalty for rates beyond 175 units/year. Economies of scale increase for all Product B components and the capability penalty placed on common components within Product B becomes increasingly important. The Product A benefit increases with increasing Product B volume because intended commonality (and the associated capability penalties) was designed into Product A. The maximum Product A unit cost benefit is reached at the Product B production rate of 200 units/year (the maximum rate considered as part of this example) and is 10%. In the offset case (two year offset), the relative benefit to Product B declines for low Product B production rates (9% at a rate of 50 units/year). The benefit/penalty to Product A's unit cost is almost negligible for all Product B production rates.

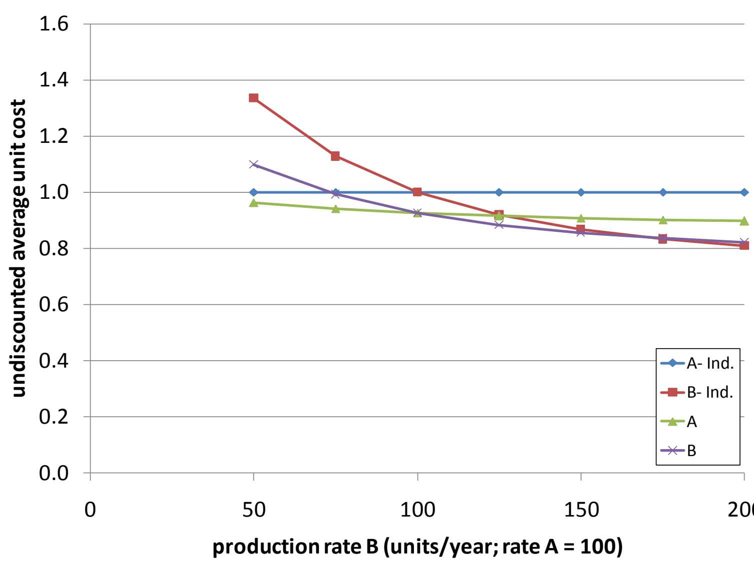

Figure 92: Average normalized unit production costs (undiscounted) for varying Product B production rates and a parallel (offset = 0) production scenario. Product A benefits from increasing Product B production rates. The Product B benefit decreases as the capability penalty of commonality increases relative to the decreasingly important gains from Product A's contribution to the common component discount; i.e., as Product B's production rate increases relative to Product A. The following assumptions are relevant to this figure: offset = 0; dr=0%; $COMM$=50%; r_{mfg}= 1. Divergence: Reuse$_{IC}$ is initially 100% and declines at the rate of 20% per year. Reuse$_{IU}$ is initially 20% and declines at the rate of 5% per year. Production duration is five years for each product.

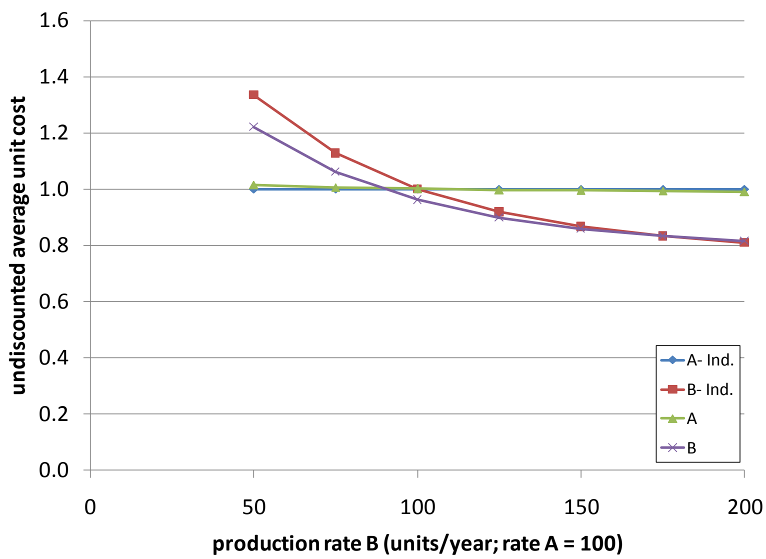

Figure 93: Average unit production costs (undiscounted) for varying Product B production rates and a two year offset. Relative to the parallel case, the offset decreases the Product B benefit of commonality for low production rates and the Product A benefit for both low and high production rates. Refer to Figure 92 for assumptions other than offset.

Production Summary

The production discussion has demonstrated the potential impacts that production offsets have on the production cost benefits and penalties of commonality. In order for a net production benefit to occur, any capability penalty must be more than outweighed by the benefits of scale and learning. Without these benefits, a production cost penalty will result.

The production benefits of commonality decrease as the offset between products increases. Parallel production (no offset) produces the most optimistic estimates of the production benefits of commonality as this case maximizes shared economies of scale benefits (duration at maximum rate) and leverages learning. Parallel production also distributes the scale and learning benefits of shared production evenly among the two product variants. Parallel production seems to be the case that is most often assumed by the literature, either explicitly or implicitly, meaning that the literature is optimistic when platform approaches are applied to products with offset production, as was observed in the seven case studies of this dissertation research. Sequential non-overlapping production provides the smallest production benefit because the only benefits beyond those associated with production of a single variant are the learning curve benefits accrued by the first program and leveraged by the second. In addition to reducing the potential benefit of common production, non-overlapping production also creates a mismatch in incentives: Product A receives no learning benefit from Product B and may incur a penalty due to excess capability; Product B receives a learning benefit that may potentially offset any incurred capability penalty. In between lays sequential overlapping production which realizes partial economies of scale benefits in addition to learning curve benefits. (See Table 19 for a summary.) The bulk of the case studies fit into this production domain. The two sequential production types (overlapping and non-overlapping) combine a lack of early production benefits with the potential costs of excess capability to present an unattractive proposition to lead variant program managers who are incentivized to maximize the profitability of their individual products. The managers of follow-on variants, on the other hand, have stronger incentives either to share in-production components or to reuse previously produced components, unless their own production volumes are so high that there is little incentive to reuse common components and to accept the associated penalties.

Table 19: Summary of potential scale and learning benefits and excess capability penalties for normalized production offsets.

	Parallel (Offset = 0)	**Sequential Overlapping (0< Offset<1)**	**Sequential Non-Overlapping (Offset ≥ 1)**
Shared Economies of Scale	Yes: maximized and equally distributed	Yes, but reduced from parallel case; equally distributed	No
Product A: Shared Learning Curve Effects	Yes: equal to B	Yes, but reduced from parallel case; < B	No
Product B: Shared Learning Curve Effects	Yes: equal to A	Yes, increased over parallel case	Yes, maximized
Penalty of Excess Capability?	Possible	Possible	Possible

6.1.4. Connecting Development and Production Costs

A framework for examining development and production costs was presented in the previous two sections. These costs can be combined (added) in order to create an accurate view of development and production costs that can be traded against other profitability factors (e.g., product sales revenues, operations revenues, and operations costs) and the impacts of commonality on these other factors. A development benefit is realized when the penalties associated with developing Intended Common components are outweighed by the benefits of reuse of these elements across more than one variant. A production benefit results when the costs of excess capability are outweighed by the benefits of shared economies of scale and learning. Obviously, a net cost reduction results when both development and production cost benefits exist and a net cost increase results when both development and production costs increase. A trade exists in cases of a benefit in one category and a penalty in the other. For example, a company may realize a development cost reduction through reuse of previously developed elements. If the manufacturing cost associated with excess capability is too high, the result creates a net loss.

The development and production equations of the previous sections can be utilized to calculate total costs for the individual platform-based products and the platform-based product family as a whole. Table 20 addresses Product A costs; Table 21 addresses Product B costs; and Table 22 provides the combined costs for the product family. Costs are calculated for each of the five component classes, which can be combined to create total costs for a given product or for the product family. Differences between these platform-based product family costs and those associated with independent designs are summarized in Table 23. Costs are calculated using the table entries listed below and the following formula:

$$Cost = basis * \{Development\ Multiplier + Production\ Multiplier\} \tag{6.26}$$

Table 20: Total program costs for Product A, by component class.

Class	Class Desc.	Cost Basis ("basis")	Product A Development Multiplier	Product A Production Multiplier
1	$IU_A \rightarrow U_A$	$(1 - COMM) * C_{dev,ind,A} * (1 - Reuse_{IU})$	1	$r_{mfg} N_A \widetilde{d}_A$
2	$IC \rightarrow U_A$	$COMM * C_{dev,ind,A} * Div$	$(1 + pen_{dev})$	$r_{mfg} N_A \widetilde{d}_A \left(1 + pen_{cap}\right)$
3	$IU_A \rightarrow C$	$(1 - COMM) * C_{dev,ind,A} * Reuse_{IU}$	1	$r_{mfg} N_A \widetilde{d}_{AB}$
4	$IC \rightarrow C$	$COMM * C_{dev,ind,A} * (1 - Div)$	$(1 + pen_{dev})$	$r_{mfg} N_A \widetilde{d}_{AB} \left(1 + pen_{cap}\right)$
5	U_B	$C_{dev,ind,B} - (1 - COMM) * C_{dev,ind,A} * Reuse_{IU} - COMM * C_{dev,ind,A} * (1 - Div)$	NA	NA

Table 21: Total program costs for Product B, by component class. (Refer to Table 20 for cost basis.)

Class	Class Desc.	Product B Development Multiplier	Product B Production Multiplier
1	$IU_A \rightarrow U_A$	NA	NA
2	$IC \rightarrow U_A$	NA	NA
3	$IU_A \rightarrow C$	$\frac{pen_{int}}{(1+r)^s}$	$r_{mfg} N_B \widetilde{d}_{AB}$
4	$IC \rightarrow C$	$\frac{pen_{int}}{(1+r)^s}$	$r_{mfg} N_B \widetilde{d}_{AB} \left(1 + pen_{cap}\right)$
5	U_B	$\frac{1}{(1+r)^s}$	$r_{mfg} N_B \widetilde{d}_B$

Table 22: Total costs for the product family, by component class. (Refer to Table 20 for cost basis.)

Class	Class Desc.	Development Multiplier	Production Multiplier
1	$IU_A \rightarrow U_A$	1	$r_{mfg} N_A \tilde{d}_A$
2	$IC \rightarrow U_A$	$(1 + pen_{dev})$	$r_{mfg} N_A \tilde{d}_A \left(1 + pen_{cap}\right)$
3	$IU_A \rightarrow C$	$1 + \frac{pen_{int}}{(1+r)^s}$	$r_{mfg} (N_A + N_B)\tilde{d}_{AB}$
4	$IC \rightarrow C$	$\left(1 + pen_{dev} + \frac{pen_{int}}{(1+r)^s}\right)$	$r_{mfg} (N_A + N_B)\tilde{d}_{AB} * \left(1 + pen_{cap}\right)$
5	U_B	$\frac{1}{(1+r)^s}$	$r_{mfg} N_B \tilde{d}_B$

Table 23: Cost differences with respect to independent development. (Common minus independent.) Benefits are listed for development, production, and combined. Integration penalties are typically assumed to be <<1, hence the reason for labeling the Class 3 Development Cost Benefit as "likely". (Refer to Table 20 for cost basis.)

Class	Class Desc.	Development Multiplier (Difference)	Develop-ment Benefit?	Production Multiplier (Difference)	Production Benefit	Net Cost Benefit?
1	$IU_A \rightarrow U_A$	0	NA	0	NA	NA
2	$IC \rightarrow U_A$	pen_{dev}	Penalty	$r_{mfg} N_A \tilde{d}_A * pen_{cap}$	Penalty	Penalty
3	$IU_A \rightarrow C$	$\frac{(pen_{int} - 1)}{(1+r)^s}$	Benefit (likely)	$r_{mfg} \left[(N_A + N_B)\tilde{d}_{AB} - N_A \tilde{d}_A - N_B \tilde{d}_B\right]$	Benefit	Benefit
4	$IC \rightarrow C$	$pen_{dev} + \frac{(pen_{int} - 1)}{(1+r)^s}$	Trade	$r_{mfg} \left[(N_A + N_B)\tilde{d}_{AB} * \left(1 + pen_{cap}\right) - N_A \tilde{d}_A - N_B \tilde{d}_B\right]$	Trade	Trade
5	U_B	0	NA	0	NA	NA

The combined view of the cost benefits and penalties of commonality (Table 23) highlights the trades associated with the various component classes. Noteworthy is the trade associated with Class 4 components. The table also highlights the potential value of reusing existing components that were Intended Unique (Class 3; always a benefit) and the negative cost impact of developing Intended Common elements that are not utilized by multiple products (Class 2). The key trade is between the normalized combination of Classes 2 and 4 and Classes 1 and 3: this trade indicates the benefit of pursuing Intended Common development relative to Intended Unique development. Given that Class 1 is the baseline, the comparison can be examined between Classes 2 and 4 and Class 3. A simple depiction of the combination of Classes 2 and 4 is illustrated in Figure 94, for development, production, and operations costs.[50] Figure 94 clearly indicates the trade associated with commonality: benefits are not a given. The figure also illustrates the negative repercussions of pursuing intended commonality that never materializes (Class 2), and the assignment of these penalties to Product A. The

[50] Operations is considered to be an analog of production for the purposes of Figure 94 and Figure 95. Capability penalties are incurred in purchasing. Economies of scale impact component costs. Labor is impacted by learning. Future work must more carefully consider operations costs.

combination of Classes 2 and 4 (Intended Common) and Class 3 (Intended Unique that becomes common) is depicted Figure 95. The figure indicates the benefit of reusing Intended Unique components and the trades associated with intended commonality. The key message in these figures: while commonality may offer benefits at the product or product family level, these benefits are not a given. Trades must be carefully considered.

Class 4: Intended Common Becomes Common

	Product A	Product B	Product Family
Development	Penalty	Benefit	Trade
Production	Trade^{o}	Trade	Trade
Operations	Trade^{o}	Trade	Trade
Net Benefit?	Trade	Trade	Trade

Class 2 and 4: Intended Common Development

	Product A	Product B	Product Family
Development	Penalty	Benefit	Trade
Production	Trade^{o}	Trade	Trade
Operations	Trade^{o}	Trade	Trade
Net Benefit?	Trade^{o}	Trade	Trade

Class 2: Intended Common Becomes Unique to A

	Product A	Product B	Product Family
Development	Penalty		Penalty
Production	Penalty		Penalty
Operations	Penalty		Penalty
Net Benefit?	Penalty		Penalty

Figure 94: A conceptual view of the trades for Class 4 and Class 2 components (left side) and their combination (right side). The claim of a development benefit for Product B requires the reasonable assumption that pen_{int} is < 1. Commonality represents a series of trades rather than certain benefits. Commonality creates likely penalties for Product A. (The superscript “^{o}” designates that overlap is required to realize a trade, benefit, or penalty. In the case of Class 4 components, a lack of overlap changes the marked boxes to a penalty.)

Class 2 and 4: Intended Common Development

	Product A	Product B	Product Family
Development	Penalty	Benefit	Trade
Production	Trade^{o}	Trade	Trade
Operations	Trade^{o}	Trade	Trade
Net Benefit?	Trade^{o}	Trade	Trade

Class 3: Intended Unique Becomes Common

	Product A	Product B	Product Family
Development		Benefit	Benefit
Production	Benefit^{o}	Benefit	Benefit
Operations	Benefit^{o}	Benefit	Benefit
Net Benefit?	Benefit^{o}	Benefit	Benefit

Figure 95: The conceptual comparison between Intended Common Development (left) and Intended Unique Development (right) indicates the potential value of reusing Intended Unique components and the trades associated with Intended Common development approaches. (The superscript “^{o}” designates that overlap is required to realize a trade, benefit, or penalty. A lack of overlap changes the marked Class 2 and Class 4 boxes to a penalty. Class 3 components provide Product A benefits, given an overlap in production and/or operations.)

The model represents more of a framework than a calculator of the "correct" answer. Parameters vary widely between programs and this variation can significantly alter the model outputs. Refer to Table 24 for a summary of model inputs, a very rough estimate of range, and the default values used in the above examples. The ranges are based on very limited case data and informed opinion. The purpose of including these very rough estimates is to indicate the broad range of values and to highlight the extreme importance of using program-specific information to evaluate the benefits and penalties of commonality. Given this outcome, it is difficult to make sweeping statements about the benefits and penalties of commonality, as these benefits and penalties are situation specific. Nevertheless, given program-specific parameters, the above equations could be utilized as a decision making aid regarding determination of the beneficial degree of common component development and production.

Table 24: Model parameters, symbols, rough indications of values, and values used for example purposes. The values are based on very limited case data and informed opinion. The intent of listing ranges is to highlight the extreme variation in these parameters: the parameters are highly specific to a given program.

Factor	Symbol	Rough Range of values	Model Uses the Following Value, Unless Noted
Global Inputs			
Discount rate	r	0 - 20%	15%
Development			
Development scope A (ind. alt.)	$C_{dev,ind,A}$	1 (normalized)	1
Development scope B (ind. alt.)	$C_{dev,ind,B}$	0.5 - 1.5 (normalized to A)	1
Intended Commonality	$COMM$	0 - 100%	50%
Offset	s	0 - 10+ years, typical: 0 - 2 years	range
Divergence	Div	50 - 100% (of IC)	range
Reuse of Intended Unique	$Reuse_{IU}$	0 - 80% (of IU)	range
Common development penalty	pen_{dev}	0 - 30%	20%
Integration penalty	pen_{int}	0 - 10%	10%
Production			
Demand A (Rate, Duration)	$D_A(n)$	Rate: 1 - 1e5+ units/year Duration: 1 - 20 years	Rate: 100 Duration: 5
Demand B (Rate, Duration)	$D_B(n)$	Rate: 1 - 1e5+ units/year Duration: 1 - 20 years	Rate: 100 Duration: 5
Ratio: mfg. unit cost to dev. cost	r_{mfg}	1e-4 - 1	1
Ratio: material to labor costs	r_{mat}	0.5 - 0.8	0.6
Learning curve	$f_{learning}(cum\_prod)$	b = 80% to 95%	85%
Economies of scale	$f_{scale}(rate)$	NA	ref. formula (Chpt. 6, Production)
Capability penalty	pen_{cap}	0 - 20%	10%

6.2. Keeping the Discussion in Context: Lifecycle Profitability

Ultimately, a company is concerned with profit, which is impacted by both revenue and cost. This dissertation has primarily examined commonality from a cost perspective, with the focus being on development and production costs. Consideration of product revenue is also critical, as commonality may have a major impact on revenue. Likewise, the potential impact of commonality on operations revenues and costs should be considered. The impact of commonality on revenue and cost is typically considered to be a tradeoff because increases in commonality tend to drive down product performance and/or differentiation. This is a well recognized outcome (e.g., Simpson, 2003). To state the obvious, any reduction in product family cost must outweigh any negative impact to product family revenue in order to provide a net benefit to overall product family profitability. If commonality is implemented in areas that have significant, negative impacts on customer differentiating attributes, revenue implications could be severe. The revenue implications of commonality are extremely complex and are not addressed within this dissertation. While small changes in commonality may have predictable impacts on revenue, larger changes can make the difference between a competitive product and one that fails in the marketplace.

6.3. Chapter Summary

This chapter has examined lifecycle offsets from the standpoints of development and production. Lifecycle offsets create an upfront development penalty that may be traded against later benefits, depending on factors such as divergence and the degree of reuse of Intended Unique components. In production, lifecycle offsets reduce the scale and learning benefits associated with commonality. Offsets in production also bias any existing production benefits toward the later products.

A key message within this chapter is the observation that intended commonality typically represents a complex tradeoff that may not be more beneficial than the alternative of reuse of Intended Unique components. Careful examination of this trade is required for each specific program context. Claims about the benefits and penalties of intended commonality, at least in the context of development and production, are difficult to make without the context of specific program conditions such as those that are approximated by the model inputs.

The simple model presented within this chapter represents a potentially useful framework for further examination of the economic benefits and penalties of commonality, although extensions are needed. This chapter has covered the costs of the two lifecycle phases (development and production) that appeared to be the most heavily weighted by the case study companies. Future work should consider frameworks for product revenues and the revenues and costs of operations. Additionally, future field research should be designed to collect real program data that could be used to further test the validity of the model presented here and to test any further extensions of this model.

7. Conclusions and Future Research

At a high level, this dissertation sought to examine the realities of commonality in the context of complex product families. The seven case studies associated with this research provided an excellent opportunity to investigate this topic. The cases highlighted the complexity of linking multiple products together through common elements (e.g., components, process, etc.) and also stressed the need to consider commonality as only one of many potential tools for improving corporate profitability.

The seven case studies associated with this research suggest several modifications to the view of commonality that is typically presented in the literature (and possibly assumed in companies), at least in the context of complex product families. First, the parallel development approach that is often, either explicitly or implicitly assumed in the literature, appears to be an accurate description of the product family planning effort but does not address the sequential (offset) nature of individual variant development that was observed in the case studies. This outcome has a negative impact on the potential benefits of commonality as was demonstrated in the discussion and model of Chapter 6. Second, the case studies indicate that plans for commonality are optimistic with respect to the actual realized levels of commonality: commonality declines with time (divergence occurs). After establishment of a plan for commonality, the environment within which the product family exists and corporate actions throughout the given product family lifecycle tend to decrease commonality over time. Divergence was shown to occur for both beneficial and non-beneficial reasons. While both reasons appear to be important to an understanding of commonality, the latter is most critical to ensuring that overly optimistic benefit estimates are not created with respect to opportunities for commonality. Incorporation of an understanding of divergence into industrial practice and academic research may contribute to improved benefit and penalty estimation and to improved lifecycle management of commonality. The case studies suggest that the benefits of commonality that are often cited in the literature may be tempered in practice and that the above two points (the presence of divergence and lifecycle offsets) have significant explanatory power with regard to this decline.

A summary of the key findings is presented below, followed by recommendations, claimed contributions, and directions for future research.

7.1. Summary of Key Findings

In short, developing Intended Common elements and realizing the benefits of doing so are significant challenges in the domain of complex product families. While many other findings are included in the body of this dissertation, those presented below represent what are believed to be the most important.

- **Lifecycle offsets are common in the development of complex product family members. Offset (or sequential) development is driven primarily by resource limitations.** Time offsets in development and production were demonstrated to be the norm within the complex product family case studies of this research. Sequential development lowers resource requirement peaks and decreases the costs of learning. Sequential development appears to be a necessity rather than a choice, as may be the case with simpler products.[51] Lifecycle offsets were demonstrated to create significant challenges with the implementation of commonality plans and in the realization of planned benefits. At the same time, offsets create beneficial opportunities for the resolution of market uncertainty in an economical manner and allow for the development of increasingly capable products through a “stepping stone” approach. In the context of complex product families, offsets appear to be beneficial to a company’s overall operations (a necessity due to resource limitations) and a limiting factor in implementing plans for commonality and maintaining these plans throughout the product family lifecycle.

- **Common assets, such as parts and processes, become similar and unique assets over time; i.e., divergence occurs.** Plans for commonality do not fully materialize in practice. In fact, the case studies have suggested that plans for commonality shift towards similarity and uniqueness due to mismatches between the needs of different market segments, technical limitations, and organizational issues associated with multiple, linked, highly complex product development programs. The “real world” of sequential product development exerts many pressures on commonality. All pressures, beyond those actions specifically taken to implement or maintain commonality, reduce commonality over time.[52] The declining commonality trend represented by divergence may be either beneficial or non-beneficial.

- **Reuse of Intended Unique elements is prevalent in industry and represents an effective development strategy to which to compare approaches to creating intended commonality.** Reuse of Intended Unique elements occurs frequently in practice and is often viewed by industry as being the default approach to product development. During the case studies, the prevalence of this type of reuse and the apparent benefits of this approach became increasingly evident as a mechanism for efficient product development. Prior development work is leveraged through either direct carryover to other product models or as a starting point from which to make incremental modifications (i.e., to create similar parts) as needed to meet future product needs.[53] Through reuse of Intended Unique elements, a company is able to effectively fulfill a current set of market needs while avoiding potentially wasted development effort pursuing future, intended commonality. Reuse of previously developed components, processes, etc. is typical in industry, although this type of reuse appears to occur in a mostly informal manner. The reuse of Intended Unique components is an important alternative to which to compare Intended Common

[51] This research did not examine simple products, although the literature tends to indicate that parallel development is both viable and common.

[52] The military aircraft program represents the possible exception, although the interview results did not substantiate the increase in commonality shown by the data. Refer to the discussions of this topic in Chapter 4 and Chapter 5 for more information.

[53] The model within this dissertation considers only carryover, not similarity for the reasons discussed in Chapter 2.

opportunities. The default comparison within the literature appears to be between platform-based development and clean-sheet approaches to independent development.

- **Similarity, or commonality at lower levels than the original decision making reference frame, offers the benefits of partial commonality (e.g., common or similar manufacturing processes) without the hard constraints of exact replication.** Similarity is almost the default result of modifications to a common component or process that result in a loss of commonality: given an organization's desire to limit resource expenditures, the original, common component or process is modified in a minimal manner to meet the new set(s) of needs. Complete replacement of a common part with a "clean sheet" design appears to be rare in practice, although confirmation of this assertion would require further investigation.

- **Development offsets increase the likelihood of divergence due to a lack of representation of the needs of all variants at the time of Intended Common element development; other limits to multi-program coordination (e.g., lack of communication throughout the product lifecycles); the high cost of backward propagation of changes to Intended Common elements; and uncertainty about future product needs.**

- **Production offsets reduce the product family production cost benefits of commonality through reduced economies of scale. Production offsets also bias the production benefits of learning toward later variants.** These trends were made clear by the case study interviews and demonstrated by the simple cost model of Chapter 6. The findings are important because they suggest that the parallel assumptions of the literature produce optimistic estimates of the benefits of commonality when these assumptions are applied to the sequential development context that was observed in the complex product family domain.

- **Corporate cultures, product development processes, and decision making approaches appear to be focused primarily on the individual product perspective, rather than the product family perspective.** The potential benefits of commonality are realized at the product family level, yet the cases suggest that decisions are often made and acted upon at the level of individual products. This approach to decision making is encouraged by product development processes that are typically focused on individual products. Beneficial opportunities for commonality/commonality retention are likely lost as was illustrated in the individual product perspective/product family perspective framework of Chapter 5 (Figure 42). Additionally, lack of, or weak, coordination causes divergence to occur almost by default.

  In five out of seven cases (military aircraft case and, to a lesser extent, automotive cases excepted), coordination was limited between the variant development efforts. To use the term of Cusumano & Nobeoka (1998), opportunities were lost for mutual adjustment, or design modifications that would have made commonality more beneficial to the later program. Little evidence was obtained during the interviews regarding specific attempts to coordinate design decisions, beyond those associated with creating initial plans for commonality and, in some cases, preliminary designs. Given a typical lack of (or weak) coordination, it is reasonable to assume that some degree of opportunity was lost, but the degree of this loss is almost impossible to quantify.[54]

- **Determining the degree of success of platform-based approaches is challenging due, in part, to a lack of comparative data.** Program data such as costs (e.g., product development investments and manufacturing cost data) and revenues can be identified for each product *that was developed and produced*. Missing from the analysis is often a credible baseline for comparison. At best, initial estimates were made for the costs and revenues of platform-based alternatives in comparison to independent alternatives. Comparison of the selected platform approach to the undeveloped independent alternative does not provide a good frame of reference for comparison. Industries that produce many products (e.g., automotive, other consumer products) are more likely to have credible baselines for comparison than industries that create very few products which may be highly customized (e.g., satellite manufacturer, semiconductor manufacturing equipment).

- **The process of creating a product family with an appropriate mix of common and unique elements is a complex and challenging process for which tools, data, and organizational practices are currently insufficient.** While this finding overlaps with previous findings, it is important to emphasize the significant challenges that are associated with creating interactions between two or more products and their development programs. Achieving effective commonality between two or more products requires significant shifts in the way a company approaches product development, ultimately requiring a different set of tools, modified data collection and reporting, and modified organizational structures.

7.2. Recommendations

The following recommendations are provided within the context of sequential development. The recommendations have been classified into those regarding economic evaluation of commonality; the lifecycle management of commonality; and other recommendations. Some of the recommendations apply equally to industrial practice and academic research, while others are more targeted toward industrial practice.

7.2.1. Economic Evaluation

R1: Develop commonality valuation techniques in order to move toward more rigorous decision making about what should/should not be common within complex product families. The simple cost model of Chapter 6 provides an initial framework. The need for valuation

[54] Examination of public information associated with product platforms (e.g., the Volkswagen and Nissan examples mentioned in Chapter 1) may be misleading in determining the degree of commonality that a company has achieved in its products (and by extension, understanding the degree of multi-product coordination). Each of the seven case studies was selected based on publicly available information that suggested the companies had implemented very strong platforms, and therefore, had strong coordination at the multi-product level. The internal views of the programs often suggested lower levels of commonality and lower degrees of coordination than were expected based on the publicly available information.

techniques that aid companies in making commonality decisions is absolutely critical. Evidence of quantitative multi-product valuation of commonality was identified in only two of the case studies, with the military aircraft program having the best developed valuation technique. The framework presented within this thesis should provide companies with a useful starting framework to which corporate cost and revenue models can be connected. Even if all data is not available, estimates of key parameters combined with available data will aid companies in moving away from "hip shots" and towards a more quantitative approach to decision making.

Establishment of formal valuation techniques will aid managers in reasoning through the very complex decisions of commonality which by definition span across two or more products. Formal valuation techniques will ensure that individual decisions that impact a common component will be made appropriately, with the potential outcome being increased (very rare within a product family lifecycle), maintained, or decreased commonality depending on which outcome provides the greatest benefit to the product family.

R2: Account for the general trend of divergence in platform-based product family planning efforts to avoid overly-optimistic estimates of the benefits of commonality. Commonality declines with time and a portion of this reduction is likely to be non-beneficial. As was previously discussed, the product family planning phase utilizes limited information, combined with a high degree of market uncertainty. Additionally, platform-based development efforts are significant efforts with commonality being a central theme. Commonality may be an explicit goal (not observed in the cases) or, more likely, is an important concept that is championed by executives and that is front and center in the platform development effort; i.e., commonality may be given "buzzword" status within a program. The case studies demonstrated significant interest in, and optimism about, commonality in the early stages of product family development, followed by much lower levels of commonality post-development.

While optimism in establishing plans for commonality is not necessarily a problem in itself, over-optimism may be a problem when the actual incurred development penalties are not outweighed by net development and manufacturing benefits in relation to the alternative of independent development. In this case, commonality produces a net loss from the product family perspective. Also, commonality may acquire an underserved negative reputation given that the initial, optimistic plan did not fully materialize.

Companies can leverage knowledge of divergence to produce more accurate estimates of the benefits and penalties of commonality. To potential paths are presented here. First, historical product data can be analyzed in order to determine estimates for the rates of divergence. Doing so requires careful data analysis that includes both Bill of Material Analysis and more importantly, but also more difficultly, design documentation analysis. The Commonality Analysis Tool presented in this dissertation provides a starting point for an automated Bill of Material Analysis. Analysis of early design data (pre-BOM existence) is more difficult from the standpoint of the existence of information and the need to manually evaluate the information, assuming that it exists. Second, companies can produce rough estimates of divergence (and other parameters) based on expert opinion. In both cases, managers must estimate the portion of divergence that they believe will (or did) result in net losses to the product family. This may be best achieved by identifying the features that clearly provided either value to the customer or significant cost reductions and "subtracting" these features from the baseline divergence rate as calculated with an analysis tool such as the Commonality Analysis Tool. While accurate estimates are desirable, they are not essential: any move away from the idealistic expectation that commonality is realized as planned is a step in the right direction.

In combination with the need to estimate the trend of divergence, a sensitivity study should also be conducted around this trend line. Important from a managerial perspective is understanding the level of investment that can be made in commonality, given the potential for divergence. If 80% commonality is pursued through the development of two products, what happens when the outcome is at the 30% level? Was the investment in commonality still beneficial? Per the prior discussions of similarity, "lost" commonality that results in similar components may still be highly beneficial.[55]

R3: Explicitly account for lifecycle offsets in the evaluation of product family business cases and their associated plans for commonality. Increasing the time offset between programs decreases the likelihood of reusing Intended Common elements and also increases the economic discounting of future expenditures. Offsets decrease, and potentially eliminate, the production benefit of shared economies of scale. Offsets also bias the benefits of learning in favor of the follow-on variant. Timing must be explicitly recognized during the product family planning phase in order to temper overly optimistic expectations of the benefits of commonality, such as may be produced by a parallel development and production assumption.

7.2.2. Lifecycle Management

R4: Extend the platform planning phase to include a more complete definition of the Intended Common elements. Increased investments in the creation of the product family plan (i.e., increased parallelism in the early planning phases) can be leveraged to more effectively investigate opportunities for commonality and, where applicable, to carefully define the Intended Common elements. For example, the process of creating improved design definitions of common elements is likely to identify and address incompatibilities between the products that would not have been uncovered in the creation of a strategy that was little more than a sketch in a presentation. Addressing these incompatibilities is most likely to result in a beneficial, common outcome, if the compromise occurs as part of a negotiation process, such as the platform planning process. At a minimum, improved platform planning will ensure more accurate estimates of the expected benefits of commonality through improved realism. The obvious extreme of this recommendation is completely parallel development of the product models, an outcome that is highly unlikely to occur given the prior discussions about resource limitations, for example. Clearly, there is a tradeoff between the costs and benefits of improved planning.

[55] Per the Chapter 2 discussion of similarity, the reader is reminded that similarity comes down to a level of reference in the design hierarchy. At a given reference level, "lost" commonality likely indicates the presence of common and unique components and or features at lower levels of the design hierarchy.

R5: Recognize the dynamic nature of platforms and plan for change. Development of Intended Common elements is not enough to ensure their benefits are leveraged. Commonality must be actively managed throughout the product family lifecycle. Note that this recommendation is not about maintaining an "iron grip" on commonality but rather about ensuring that commonality is properly managed. The elimination of commonality for beneficial reasons should not be discouraged.

R6: Assign a dedicated platform owner to ensure that opportunities for commonality are identified; properly evaluated; implemented if beneficial; and managed throughout the lifecycle. Platform ownership should exist throughout the product family lifecycle. Formal ownership of commonality is one potential way to ensure that opportunities for commonality are identified, evaluated, and acted upon if beneficial. While the military aircraft case suggests that formal ownership may not be an absolute requirement (given a commonality culture), formal ownership appears to be an effective way for companies to start the transition from independent product development to platform-based product development. The platform owner should establish and maintain the commonality strategy; document and communicate requirements for each variant; conduct product family trade studies across common or potentially common elements (i.e. studies that account for performance; development and variable costs; risk; and schedule); and act as the overall design authority for common portions of the products. This person should have decision making authority that is at least equivalent to that of an individual program manager. The platform owner should be involved in the negotiation of any platform changes that are required by an individual program, keeping in mind the higher level goals of the product family. While senior managers may perform the above duties informally, their breadth of responsibility does not allow them to focus on commonality.

R7: Consider establishing an owner or owners of future variants in order to ensure that future variant needs are represented during establishment of the platform (Intended Common elements). Individual variant needs must be represented in order to ensure proper tradeoffs are made, or at least considered, during development of the Intended Common elements. Representation is especially important in the sequential development setting observed in the case studies. Assigning people and other resources to future product development efforts may not be typical, yet is critical to improving the likelihood of reusing Intended Common elements in future products. Formal ownership of future variants is one path to achieving this goal. The recommendation of formal variant ownership is complementary to the prior recommendation of formal platform ownership. Implementation of both recommendations provides a formal structure for ensuring that development is considered from the product family perspective. These recommendations are also likely to drive longer-term cultural changes.

R8: Evaluate the relative power balance between individual programs and the functional teams charged with supporting these programs. Consider increasing the decision making influence of functional teams if they have been relegated to pure support of independent program decision making. Functional teams have strong internal resource-driven incentives to pursue or maintain commonality and these teams also have the knowledge to do so. What the functional teams typically do not have is the decision making authority to challenge or override program level decisions.

R9: Beneficial and non-beneficial sources of divergence must be recognized and acted upon, although in different ways. Beneficial opportunities for divergence should be recognized and allowed to occur, while attempts should be made to minimize non-beneficial divergence. Beneficial opportunities for divergence should be recognized and allowed to occur. As was discussed previously, beneficial divergence results in net benefits to the overall product family through either increases in revenue[56] or decreases in cost. Failure to recognize and act upon required or beneficial opportunities for divergence may result in a "TFX Situation" in which commonality had become an end objective that penalized the program rather than having been utilized as a means to an end. Managerial control must not be so strong as to resist real improvements that contribute a net profit to the company.

Non-beneficial divergence should be minimized in order to avoid lost benefits of commonality that are not offset by increases in revenue or other cost benefits. Minimization of non-beneficial divergence can be achieved through formal management of commonality, organizational changes, and cultural shifts.

R10: As time offsets between products increase, focus efforts on the intelligent reuse of existing assets rather than on enabling future commonality. Intelligent reuse encourages efficient resource utilization in an organization, especially in the presence of high degrees of uncertainty. While this recommendation is not novel, the informal approaches to reuse that were observed during the case studies suggest that the benefits of reuse have not been fully realized. Creating processes and cultures that encourage reuse and that allow for new development by exception is likely to produce significant benefits, possibly even greater than those associated with Intended Common development. (Refer to the trade descriptions in Chapter 6.) People intuitively understand the benefits of reuse and the cases have demonstrated that reuse is already a natural approach to development. Encouraging and even formalizing reuse represents an incremental change within most organizations; i.e., improving reuse is much less "invasive" than focusing on Intended Common development. The largest barrier to improved reuse is likely cultural: encouraging reuse within teams that are valued for their ability to innovate may be a significant challenge.

Enablement of future opportunities for commonality (development of Intended Common elements) requires very real up front penalties to be paid and requires the ability to "predict the future" with enough accuracy to realize gains on a portfolio of pursued opportunities for commonality. As uncertainty increases, the likelihood of realizing a benefit from this approach decreases.

R11: Ensure processes such as the Product Development (PD) Process and Engineering Change process require formal consideration of commonality and the impacts changes to commonality have on the entire product family. PD processes are typically concerned with the

[56] Performance may serve as a surrogate for revenue, as was the case in the TFX program.

development of individual products rather than product families, as was discussed earlier in this chapter. Given this situation, the PD process implicitly encourages decision making from the perspective of an individual product and may produce irrational decision outcomes from the perspective of the product family. Several suggestions are listed below for improving typical PD processes.

- Consider formal approaches to reuse of prior development. The PD process can be designed to require examination of existing alternatives prior to allowing new development. Tools must also be created and made available to enable designers to reuse existing parts, processes, etc. A development benefit of reuse only exists if the cost of the search for an existing alternative is less than the cost of developing a replacement.

- Consider formal approaches to Intended Common development. At the highest level, require the establishment of a commonality plan as a PD process deliverable. The plan should define Intended Common elements along with their anticipated benefits. Marketing should be required to report on the potential revenue impacts of the commonality plan. Marketing assessment of the plan will help to ensure that engineering teams are not conducting unnecessary optimization that may provide a benefit to the customer without providing the manufacturer with increased profit. Follow-on variants should be required to follow this plan or to provide justifications for deviations, as any move away from commonality should provide a net benefit to the product family. The purpose of recommending a formal approach to managing Intended Common development is not to maintain the previously mentioned "iron grip" on commonality, but rather to ensure its proper consideration. The current default appears to be a lack of, or weak, consideration of commonality and the default outcome is uniqueness.

- Ensure that the business case is analyzed for the entire product family, rather than for the individual product under development. Ensure that a sensitivity study is conducted with respect to investments in commonality and actual outcomes.

- Require "tagging" of common elements. (Refer to next bullet.)

R12: "Tag" elements as either Intended Common or Intended Unique, starting with the conceptual stage of design and retaining this attribute throughout the lifecycle. Record decision outcomes and explanations for these outcomes. "Tagging" provides a reliable way of ensuring that commonality is *examined* and also allows for historical assessment of divergence. A common element should automatically trigger a different set of development, release, and lifecycle management practices. For example, design modification of a common part should trigger analysis of the impact this part change has on all variants that utilize the part, not only the variant that initiates the change. Explicit consideration of commonality helps to ensure that divergence occurs only for beneficial reasons. Tagging should be viewed as triggering a discussion about commonality rather than as a means of retaining commonality.

In addition to serving as a lifecycle management tool, tagging along with recording information about decisions influencing the commonality attribute of a given component would also allow assessment of the actual rates of divergence for a given program and the reasons for this divergence. This information could be combined with other part attributes to improve commonality planning and estimation for a company's future product families.

R13: Consider establishing and tracking commonality metrics, but do so with caution. Commonality indices, such as those reported in Thevenot & Simpson (2006) may be utilized to track commonality levels, although these indices may create some risk of erroneous decision making when utilized as program management tools. As has been repeatedly discussed in this dissertation, commonality is a tool, a potential means to an end of corporate profitability. Tracking commonality metrics immediately raises the question of the ultimate management goal. Clearly the goal cannot be maximization of the commonality level, minimization of divergence, etc. Important are the individual commonality decisions rather than the overall trend. That said, the use of historically tracked commonality indices is likely valuable in the presence of limited information, such as the situation encountered during the product family planning phase.

Tracking commonality metrics may also be useful in cases where organizations are attempting to raise awareness about commonality and the need to consider commonality. Tracking the metrics and citing specific examples of increases, retention, and decreases of commonality during program meetings is likely a beneficial undertaking in terms of raising awareness and educating employees.

7.2.3. Other

R14: Create a "commonality culture" that ensures that commonality is considered and implemented if beneficial. Consider decisions at the product family level, in addition to the level of the individual product. Ensure a culture of designing new by exception rather than by default. Focusing solely on the profitability impact that a decision has on an individual product may or may not provide the best outcome for the product family as a whole, the latter of which is likely better aligned with the needs of the corporation. (Refer to Figure 42 in Chapter 5 along with the relevant discussion.) Focusing on the benefits to individual products may produce losses at the product family level. Focusing on the benefits to the product family may produce seemingly irrational decisions at the individual product level; decisions that are appropriate for the product family as a whole. A cultural shift is critical to efficient product development in companies that produce multiple products. While reuse is natural in companies that develop products, it is not always a consistent strategy. Reasons for the observed inconsistency may be linked to lack of awareness of potential matches (i.e., a team or employee's inability to find the existing match); lack of incentive to utilize potential matches; and lack of willingness to use these potential matches due to a team's desire to innovate and improve, rather than to reuse. Additionally, reuse may not be feasible, given issues of compatibility between products. (In many situations, the outcome of incompatibility is hypothesized to be the creation of similar, rather than unique, designs.)

R15: Make the connection between an individual employee's objectives and the *potential* benefits and penalties of commonality. As has been demonstrated within this dissertation, commonality has the potential to impact very tangible goals, of which the focus here has been cost. To the extent that commonality is tied to goals such as those associated with revenue and cost, employees will approach commonality as a potential tool worth considering.

R16: Identify and fund beneficial opportunities for developing common building blocks outside of individual product development programs. The value of this approach increases with increasing certainty of needs and increasing similarity of needs between products. In the case of most complex products (at a minimum, those studied within this dissertation), Intended Common development proceeds as an integral part of the lead variant development program. The resulting Intended Common outputs are tailored to each individual product and are less suitable as building blocks for future derivatives. Each program modifies the prior program's outputs with the goal being "optimization" for the current program.

Pursuing common building block development that is external to individual product development programs may increase component (and process) reusability by avoiding the product-specific optimization that occurs within an individual product development effort. The case studies suggest that common building block development efforts are limited in practice and that successful efforts appear to be linked to high cost components that had required development investments that were clearly beyond the resources of a typical individual product development budget. Care must be taken not to over-invest in Intended Common building blocks, especially in highly uncertain environments. In these instances, the costs associated with Intended Common development and manufacturing combined with the higher rates of divergence are likely to make this approach unattractive; however, pursuit of common building blocks in relatively stable environments with high similarity between the needs of the individual variants may provide attractive returns if properly managed.

7.3. Contributions

The main contribution of this dissertation is an improved description of platform-based development in the context of complex product families. Through a combination of case studies and modeling, this dissertation has taken a step in the path towards building a better understanding of the benefits and penalties of commonality and the managerial actions that influence them. Specific contributions are summarized below.

- A **description of complex, platform-based product family development** has been created based on the seven case studies. This description is summarized as sequential development with high degrees of divergence and a stronger emphasis on reuse than on future enablement of commonality. This description provides a significant amount of contrast with the predominantly parallel views (either explicit or implicit) presented in the literature. The description presented within this dissertation should contribute to improved alignment between academic research and practice. The description should also aid companies in creating better estimates of the benefits and penalties of commonality and in managing commonality throughout the product family lifecycle.

- An in-depth **description of the phenomenon of divergence** was presented (Chapter 4 findings and Chapter 5) and was supported by case study evidence, both qualitative and quantitative. The description differentiates between beneficial and non-beneficial divergence and includes discussions of the potential sources and enablers of divergence. Critical to both research and practice is the observation that divergence results in the need for discounting of the expected benefits of commonality. The divergence description presented here should improve academic and industrial understanding of the evolution of commonality over time and the benefits of commonality in light of this phenomenon. This understanding is important to both business case evaluation for product families and to the proper lifecycle management of commonality.

- A detailed **description of lifecycle offsets** was presented (Chapter 4 findings and Chapter 6) in the context of the impact that offsets may have on the economic benefits and penalties of commonality. The description of lifecycle offsets, supported by the case study interviews, highlights a common mode of complex product development that appears to be underemphasized in the literature. The simple cost model included with the description illustrates in a quantitative manner several of the key trades in development and production. For example, production benefits at the product family level were shown to decline with increasing offset and to increasingly favor the later variant. The description and model should aid both academic researchers and corporations in evaluating the economic benefits of commonality in a more realistic (less optimistic) manner. Beyond evaluation, recognition of the sequential nature of development may lead to improved management practices such as the assignment of "official" owners of the platform and the assignment of owners of future variants who are charged with representing these variants during the initial lead variant development process.

- **Seven case studies of complex product families** were conducted and documented. These case studies provide a rich set of insights into the realities of complex product development practice. (Refer to Chapter 4 and the Appendix.)

- A **conceptual framework** was created to describe the difference between development intent and actual outcome. (Refer to Chapter 2, Figure 8.) While simple, this five-class framework has significant explanatory power with respect to the actual outcomes of platform-based development. The framework serves as a reminder that while explicit attempts to enable future commonality (i.e., Intended Common development) may produce common outcomes, these outcomes are not a given. Additionally, commonality may arise from an organization's tendency to reuse preexisting assets that were developed for other purposes (Intended Unique). The framework helps to highlight the need to consider these typically unrecognized outcomes and serves as the basis for the simple cost model.

- A **simple cost model** (Chapter 6) was created to demonstrate the development and production cost impacts of commonality in the context of divergence and lifecycle offsets; i.e., to investigate the cost benefits and penalties of commonality. The model is based on the key relationships and factors identified during both the literature review and case studies. The model demonstrates the cost benefits and penalties of commonality in relation to the alternative of independent development with reuse. The model also demonstrates the tradeoff nature of this relationship: there are few generally "correct" answers meaning that the benefits are situation dependent. While simple, the model appears to have significant explanatory power and achieves this explanatory power in a general way. (The reader is reminded of the application-specific context of much of the existing engineering literature.) The model can be utilized as a "management simulator" to demonstrate key trades and as a starting point for building corporate economic models of platform-based product families.

- A **tool for the automated analysis of commonality** within complex product families (the Commonality Analysis Tool, as described in Chapter 3) was developed in support of this research. This tool may serve as the basis for more advanced analysis tools and methods that calculate more advanced metrics, analyze commonality at different levels of the Bill of Material hierarchy, etc. (Refer to the next section.)

7.4. Future Research

While this research has identified divergence and lifecycle offsets as critical, yet often overlooked, factors with respect to platform-based development practice, many avenues exist for further research into the general topic of platform-based development; the benefits and penalties of commonality; and the specific context of complex product families. Several proposed directions for future research are listed below.

- **Further develop the benefits and penalties discussion. Include a more detailed treatment of product revenues, operational costs, and operational revenues. Address the lead time and risk impacts of commonality. Examine multiple stakeholder perspectives.** The topics of product sales revenues and operations (both costs and revenues) were deemphasized in this dissertation in order to control research scope and in order to address what were perceived to be the main potential benefits of commonality: development and production cost reductions. Clearly, product sales revenues and operations must be addressed in greater depth to create a holistic picture of the economics of commonality.

  Additionally, the benefits and penalties discussion should also be explicitly examined from product lead time and risk perspectives. Product lead time impacts product revenues. Risk potentially impacts revenue (e.g., failed or inadequate product) and cost (e.g., warranty issues). The implicit assumption in this dissertation was that lead time and risk ultimately translate into economic issues but a deeper treatment of the subject would provide additional insights.

  While this dissertation research was conducted from the manufacturer perspective, the manufacturer's interests are not always aligned with its stakeholders such as suppliers and customers. Cost reductions associated with commonality may be retained by a manufacturer, rather than being passed on to, or shared with, customers. Additionally, and as described in the semiconductor manufacturing equipment case, different organizations may have incentives to pursue different commonality strategies. This complexity was not addressed in this dissertation and represents a critical area for further research. An examination of customer benefits and penalties would contribute to an understanding of the revenue implications of commonality decisions, a topic that was only tangentially addressed here.

- **Conduct research into the types of data that should be collected to support the measurement and management of commonality.** Determining the ultimate success of a platform-based strategy was found to be nearly impossible during this research. Data availability and quality were limited. New research is needed into the types of data that companies should collect to enable evaluation of the degree of success of their platform-based development programs. Tagging and tracking Intended Common components (refer to the recommendations of this chapter) are potential suggestions. Much more effort is needed in this area.

- **Attempt to quantify divergence for a specific company or industry sector. Measure divergence starting with the product family planning phase (if possible) or preliminary design phase.** Divergence could be further characterized for specific companies and programs. While work along this line was started as part of this dissertation, the results were limited by data availability and data quality. Detailed characterization was also somewhat out of scope in the current research program: this dissertation investigated the existence of the phenomenon of divergence and created a description of this phenomenon. By leveraging the results of this dissertation, a more focused follow-on research program with a field research design explicitly aimed at quantification of divergence would provide additional insights into the patterns of divergence, the sources of divergence, the enablers of divergence and the ultimate impact of divergence. Success would depend on identifying a company or companies that have excellent design records and product data. Future work to further characterize divergence would likely require a broad survey of potential participants, followed by down-selection to ensure adequate data quality would be available for follow-on case studies.

- **Extend the simple cost model to increase the model's explanatory power.** The simple cost model can be extended in a number of directions. Several suggestions are listed below.
    - Add a revenue module that accounts for commonality levels between products.
    - Address operation costs, operations revenues, and production overhead.
    - Construct stakeholder views of the model to examine tensions between stakeholders; for example, the tension between the manufacturer and customer.
    - Account for the fact that multiple prior products may serve as sources of reuse for each product variant development program, including the lead variant.
    - Extend the model to include more than two product variants.

- Incorporate multiple divergence trends (e.g., linear, exponential decay, composite) and explore their impact.
- Consider the potential impact of lost learning that is associated with a pause in the production of a common element.
- Examine the impact of different capability penalties (pen_{cap}) on the manufacturing costs of each product variant.
- Attempt to build a connection between the model factors and actual case study data. This initial research effort was aimed primarily at description. The model was one output of this descriptive work. Follow-on research, that utilizes the results of this dissertation as a guide, could be designed to collect relevant data for the model and to further test the model's validity.

- **Refine the Commonality Analysis Tool to include analysis of commonality at higher levels of the assembly hierarchy.** Doing so would provide additional information about commonality within product families. The degree of integrality/modularity of the platform is hypothesized to potentially influence the benefits and penalties of commonality.

- **Examine the concept of similarity in greater depth and compare this understanding to the findings of this research.** Exact commonality is a high standard to meet and, as illustrated in this research, tends to go away with time. What remains, in many cases, are similar components, processes, etc., that share underlying concepts, knowledge, features, etc. Research into the benefits and penalties of similarity is a complex topic that could have significant implications for industry. As an example of the complexity of this topic, the measurement of similarity is in itself a very difficult topic to investigate.

As has been repeatedly demonstrated throughout this dissertation, the benefits and penalties of commonality represent an extremely complex set of tradeoffs that reach across an extended organization. These trades are not well understood, yet commonality is a strategy pursed by industry and heavily researched by the academic community. Commonality offers the potential for increased profitability but must be better understood in order to ensure that decisions to implement commonality in product families consistently produce a net profit increase. Rather than claiming to have provided a definitive assessment of the benefits and penalties of commonality, this dissertation claims to have made a contribution within this complex topic. Further research in this area has the potential to have a high degree of practical importance to a broad array of companies and industry sectors, while also making contributions to under-addressed areas of the academic literature.

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9. Appendix

9.1. Case C: Commercial Aircraft Family

9.1.1. Introduction

The commercial aircraft industry is a challenging business due to a combination of demand uncertainty; the presence of strong competition; and the extreme costs and complexity of aircraft development and operations. In terms of cost and complexity, large (multi-billion dollar) investments must be made to support the development of a complex system that entails collaboration across a large extended supply chain. Operational excellence in manufacturing is required in order to build such a complex product in a repeatable, cost effective manner.

The development of a new major model entails a significant economic risk, with new aircraft development often being equated to "betting the company." The high investments and risks associated with the development of a new aircraft drive aircraft producers to pursue a product family approach that leverages the large initial investments and retired risks across a family of related derivative products. This approach entails development of the first, or lead variant, with follow-on variants being developed as the initial model generates revenue and gains operational experience and as the market is better understood.

Case C examined the development and current status of a highly successful commercial aircraft family. Four of the variants are discussed in this summary and are referred to as "Small," "Medium," "Large," and "Extra Large" to indicate typical passenger capacities. It is important to note that all variants in the family are not reported in this summary. See Figure 96 for a rough layout of the family development history.

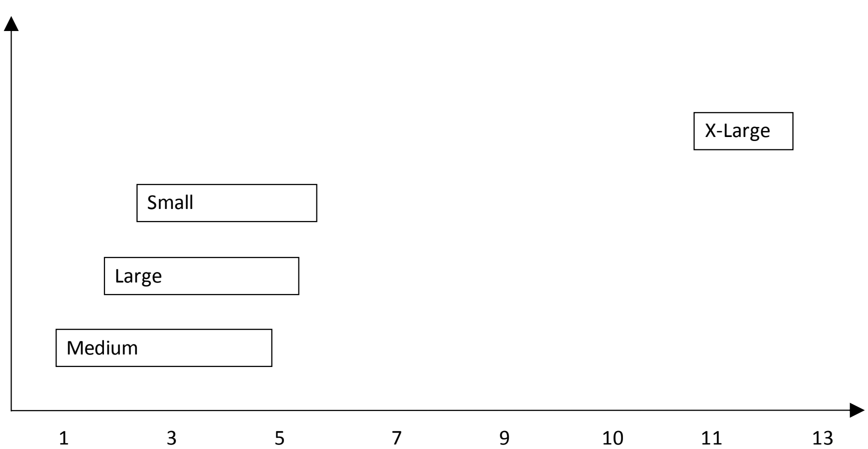

Figure 96: Product Family C development. Bars indicate time period between program launch and flight certification.

9.1.2. Brief History

Product Family Vision and Development of Initially Planned Models

Program C represented the opportunity to redesign a highly successful product family given significant prior development and operations experience with related aircraft models. Production and operational experience with an existing global fleet of aircraft provided Company C with a significant amount of field experience and customer feedback, both of which were directly relevant to development of the new family of aircraft. As with other development programs, Company C solicited feedback from a broad array of customers, both current customers and new potential customers.

Market research and prior experience clarified the need for a broad range of incremental improvements to the existing aircraft. Increased airspeed was desired. Transcontinental range was required. Decreased operating costs were extremely important along with decreased community noise. Increased altitude was desired in order to improve point to point routing flexibility, which would lower fuel burn and contribute to decreased operating costs. Many customers were flying existing variants and wanted to ensure that the new models had a common type rating, which would minimize or eliminate pilot recertification requirements. In order to address these customer needs, the existing aircraft architecture was retained, with many evolutionary modifications being planned in order to meet the new requirements. Although the new aircraft family leveraged prior heritage, there were never any formal constraints placed on Product Family C development with respect to reuse of this prior heritage.

The original Product Family C vision consisted of developing three models (Small, Medium, and Large) in a sequential manner. The aircraft would be developed sequentially due to the large amount of resources required to create a new aircraft: multiple models couldn’t be developed in parallel. The need to develop one Product Family C model at a time was further reinforced by the existence of other aircraft programs within Company C and the need to share resources across these programs. Development was initially planned to start with the Large model, although the development order was changed due to significant early customer orders being placed for the Medium variant. Preliminary design work originally conducted in support of the Large model was heavily leveraged to produce the first variant, the Medium model.

Development of the Large variant followed the Medium variant, and utilized this aircraft as a baseline. Fuselage “donuts” were added fore and aft of the main fuselage. The body was strengthened in many areas through increased gage thicknesses and modified machining paths for metal parts. Likewise, the wing was strengthened through gage changes and the addition of several extra stringers. Heavier tires, wheels, and brakes were designed to replace the Medium variant’s parts.

The Large variant’s wing was based on that of the Medium variant, although modifications were required in order to meet the heavier load requirements of the larger aircraft. The wing team’s approach was to start with the Medium design as a baseline with metal being added in order to meet the new load requirements. The result was a series of very small but widespread metal thickness (gage) increases that were spread over the entire wing, with the net weight adder being significant enough that it could not be accepted on the lighter aircraft models: neither Company C nor its customers were willing to carry this extra weight in the smaller aircraft variants.

“Small” model development entailed the removal of the fore and aft fuselage donuts. The empennage was carried over as the Small model characteristics actually drove the tail design due to the shorter moment arm that tail forces act upon in this configuration. Note that carryover of the basic feature is unlikely to equate to carryover of the exact empennage components although this statement was not confirmed during the interviews.

Given the upfront desire to develop a family of aircraft, commonality was always a part of performance discussions, particularly during preliminary design, although performance was definitely the highest priority. The challenge was in addressing the very tangible connection between commonality and weight which ultimately led to a typically negative relationship between weight and cost. Commonality by definition requires that a given part or module meet the superset of requirements placed upon it. Unless required capabilities are exactly matched, each variant has different needs. In the case of commonality, the variants with a lower capability requirement are penalized due to the need to accept more capability than required.

The preliminary design team calculated commonality penalties for each of the three aircraft designs and found that all three aircraft structures would incur commonality weight penalties with respect to a truly optimized design. As an example of different variants driving maximum requirements, thrust was driven by the Large model, while empennage requirements were driven by the Small model due to the reduced moment arm afforded by a shorter fuselage.

The discussion about commonality was held often, although the end outcome was typically an inability to justify the benefits of weight addition (in support of commonality) from the customer perspective. The result was the creation of many similar, but not common, parts and modules. Given the strong emphasis on weight and weight’s strong linkage to cost, it pays Company C to pursue point optimization of each variant as long as development costs do not spiral out of control. The pursuit of “point optimal” solutions was most evident in the structural design of the aircraft which accounts for a significant fraction of aircraft weight and is influenced by load requirements. The wing development effort was one example. A new wing was created for Product Family C in order to increase speed, range (increased fuel volume), and cruise altitude (increased wing area). The preliminary design team had identified significant penalties associated with a common wing. In addition, the wing team often worked under a tight schedule, having received wing loads late. Designing a common wing would have added complications to the development effort and in the end, the wing was similar but optimized for each variant.

A key element of the Product Family C strategy, and one in which commonality did play a major role, was in the use of a new common engine with selectable thrust. The common engine strategy may at first seem to run counter to the previously described “point optimization” approach to heavy components such as the aircraft structure, but in the case of the engines, commonality was deemed to provide a significant benefit. Smaller aircraft accept a weight penalty due to carrying the more capable (but thrust limited) engine but the operational cost associated with the weight penalty is more than offset by a longer on-wing time due to lower thrust levels, i.e., the smaller aircraft exposes the engine to a less demanding operational environment. The net result is an overall savings for all variants. It is also important to note that engine development costs are extremely high and development of multiple variants would have been very costly: unlike structural optimization, the penalties of engine uniqueness were sufficiently high enough to drive commonality into the product family.

While the goal was to change as few things as possible across models, the team ultimately pursued "point optimized" designs for each variant that leveraged common tooling and processes. Through this approach, Company C would realize internal cost structure improvements due to common process without the negative impacts that exact common parts would have had on operating costs. As an example, scalable tooling was designed for fuselage assembly. This tooling scales in length to accommodate the different variants and is designed around self-fixturing concepts. The use of flexible tooling represents a significant cost savings as unique rigid tooling is no longer required to support each variant.

The Addition of a Highly Successful Variant that Was Not Included in the Original Product Family Plan

Years after the initial product family plan had been created, the need for a higher passenger count than was originally anticipated was realized. Marketing identified performance as the utmost priority for the Extra Large ("XL") model and major development was undertaken in order to reach the required market needs. The majority of the aircraft program (approximately 70%) was focused on the structural modifications required to support increased passenger counts and to meet the associated emergency exit requirements. The development team established a corresponding weight cost that was several times higher than that of the original Product Family C variants. While the goal was to reuse as much as possible, the stringent dollars per pound threshold drove design optimization decisions that were justified from the market perspective. As with prior variants, common tooling was always an end goal: manufacturing tooling constraints were always treated as hard constraints within the XL program. The limited tooling investment (approximately 5% of the total XL program budget) indicates that the common tooling strategy was highly successful.

In terms of design, the XL's increased gross takeoff weight required greater thrust. This thrust was achieved through utilization of the maximum available engine thrust combined with innovative improvements in low speed aerodynamics that provided the required thrust offsets. In this manner, a core common element, the common engine, was retained while still enabling the required differentiation in aircraft capability.

Additional changes spanned across the entire aircraft and were significant in scope. As with prior models, every major part on the XL wing was modified (thickened) to support the higher loads. Fore and aft fuselage segments were also thickened for the same reason. A pair of exit doors was added aft of the wings to meet the emergency egress requirements. Most systems were either carried over directly or were modified so that they would be pin configurable for the XL.

The XL program was somewhat unique in that it occurred years after the initial product family vision had been established and years after the first flight of the prior Product Family C variant. This gap created some challenges with the loss of original team members and their knowledge, although the Deputy Program Manager believed the impact of this knowledge loss was relatively low.

The Deputy Program Manager for the XL felt that commonality decisions were relatively easy to manage due to the team's understanding of the importance of commonality combined with the proper decision making behavior driven by the cost per weight metric. The corporate culture around commonality and reuse was strong and the existence of other aircraft development programs meant that resource constraints drove commonality as a default approach to development. Commonality with existing models was the starting point with moves away from commonality being carefully scrutinized. At the end of development, the program had increased the total unique part/assembly count of the product family by only 14%. The success of the limited part increase is significant given the major performance changes required for the XL variant.

9.1.3. Observations

Product Family C has enjoyed strong market success in terms of actual aircraft deliveries, aircraft order backlog, and aircraft performance. Within the aircraft family, commonality has always been viewed as a potential tool for controlling costs (both investment and production), rather than as an end goal.

Several specific observations are listed below:

1) **A well thought-out vision was created for the first three variants of the product family. Larger aircraft than initially envisioned were added to the family at a later date, underscoring the need for flexibility in product family planning.** The vision included performance attributes and module concepts that were supported by high level analyses and conceptual design work. Detail design was out of scope. In terms of the original three variants, the vision was well-matched to the actual program outcome. Conceptual layouts materialized; many systems were shared per the plan; and airframe structures were highly optimized due to the strong impact of weight on operating performance. It is important to note that the addition of unplanned variants to a family is a common occurrence in platform-based product development. Market needs change during the course of development, triggering major changes to an existing model or the development of new models, as was the case with this product family.
2) **Carryover from prior product models was not a requirement for Program C and was viewed as a potential impediment to meeting the new market requirements. Additionally, little benefit was expected from the reuse of prior components as production overlap between old and new models was limited.** The team recognized that

the incremental advancements required by customers would be extremely difficult to achieve if design decisions were overly constrained by existing products. The approach was to leverage new systems developments and incremental airframe advancements across the Program C family members, rather than leverage existing, but dated, elements from prior models. The development savings associated with reuse were outweighed by the revenue benefits of an improved match between the aircraft models and market needs.

3) **The Program C product models were developed sequentially, primarily driven by the resource limitations of such a large, complex endeavor.** While the high level conceptual design of the aircraft family was completed in parallel, development occurred sequentially, primarily due to the tremendous resource requirements associated with detail design and development: supporting multiple efforts would have created serious resource loading issues.

4) **Product Family C models heavily leverage common tooling and processes. "Commonality of process IS an end goal." The benefits of common processes are well understood and vigorously pursued across the organization.** Everyone in the organization was aware of the need to pursue process commonality. While commonality of process is an end goal, and vigorously pursued, manufacturing (e.g., assembly and inventory) has been unwilling to sign up to manufacturing cost reductions driven by common part opportunities. The lack of manufacturing feedback undervalues the benefits of commonality and overvalues the benefits of optimization.

5) **The trades between aircraft operating performance (primarily cost) and commonality are well understood within Company C. In the case of structures, design decisions typically favor weight optimization over commonality due to the large operating cost impact, although exceptions exist.** Weight tradeoffs have clearly been analyzed by the design teams and the cost of weight is well known to both Company C and its customers. Each program establishes cost per pound metrics that drive decision making.

   Interview discussions related to the product family vision provided numerous examples of tradeoff analyses that involved aircraft weight penalties induced by commonality. These weights were translated into operating cost impacts, with the result typically being a decision to optimize airframe components rather than maintain commonality across the family. Operational costs are directly impacted by commonality and represent a significant fraction (approximately half) of the total lifecycle costs for a given aircraft. Reducing operating costs is often linked with reducing aircraft weight, creating a direct tension between commonality and reducing weight.

   The aircraft team does not blindly pursue weight optimization, as was evidenced by the common engine example. The engine is an interesting example of a decision in support of commonality. The same engine is utilized for all Product Family C variants with thrust being selectable. Use of the larger engine on a smaller aircraft results in lower operating costs due to the longer on-wing time enabled by the less demanding operating scenario. In this case, a larger engine has been determined to provide benefits to all variants.

6) **Company C and its customers realize different penalties and benefits from commonality.** For example, Company C may be concerned with commonality across its current family of production aircraft, while a customer is concerned with commonality across a fleet of different models of aircraft purchased at different times in history. Customers may drive "Copy Exactly"-like[57] policies that are beneficial from the customer point of view but drive divergence from the standpoint of Company C's product family. For example, maintaining a specific configuration for a given airline maintains commonality across the airline's fleet, while increasing the diversity of products offered by Company C.

   In some cases, the benefits are aligned, representing win-win situations. Alignment does not necessarily mean realization of the same benefits. For example, a weight reduction may reduce Company C's manufacturing costs while reducing a customer's operating costs.

7) **Differences in the makeup of Company C's customer base introduce variability into the customer benefits and penalties of commonality. Commonality decisions may be contradictory from different customer perspectives.** Customers may operate single or multiple Product Family C models. Given this potential mix, commonality decisions present different benefits and penalties to the various customer types. Consider for example, a customer that operates only one Product Family C model. The only incentive the customer has to pursue commonality is the indirect incentive of lower purchase, service, and parts prices potentially passed along by Company C. Aside from these benefits, the single aircraft operator has little incentive to push commonality: optimized components will result in the best direct operating costs for this customer. As a second example, several interviewees mentioned that some mixed model fleet operators choose to install the tires, wheels, and brakes from a larger Product Family C model onto their smaller Product Family C model. In this example, the decision to optimize both sets of parts for each aircraft may not have made sense from the standpoint of mixed fleet operations but would be acceptable, likely desirable, to a customer that flies only the smaller model.

8) **The relative stability of Company C's employee base (low turnover rate) is a strong enabler of commonality.** With the exception of the newest model, the same team developed all of the Product Family C models, reducing the degree to which "wheel reinvention" occurred; minimizing the challenging of previous decisions; etc. Additionally, a single project engineer owned all models and the same Vice President was in place for all variant development efforts.

9) **The bulk of Company C's organization structure is based on functional teams rather than program teams. Program teams are utilized to create new variants. The resulting designs are then transitioned into the function-based supporting organization. Commonality appears to be reinforced by the functional organization structure because the functional teams have strong incentives to reduce the complexity of the product family and have the cross-product knowledge required to do so.**

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[57] "Copy Exactly" refers to Intel's strategic goal of exact replication of everything within a proven factory layout. For example, once a piece of capital equipment is qualified, the supplier must reproduce the design exactly, or make changes in a very controlled manner, with Intel's consent.

9.2. Case D: Business Jet Family

Company D is a highly successful business jet manufacturer, known for its product quality and superior support. Company D provides its customers with the opportunity to customize all aspects of the aircraft that impact the customer experience which primarily means the aircraft interior. The popularity of the Company D's aircraft has created a production backlog several years long and has enabled the company to maintain strong margins in the face of increasing competition.

Company D customers include corporations (80%), the military (15%), and high net worth individuals (5%). The purchase of a business jet tends to be viewed as a business tool and as such, purchase justifications are fairly sophisticated, often considering total cost of ownership. Customers typically operate fleets of from one to seven aircraft. A large customer flies five to seven aircraft with most fleets consisting of multiple aircraft models, spread across Company D and its competitors. Fleet operators are often interested in common operations (pilot training and maintenance).

Common designs are often a challenge with regards to the flight performance aspects of an aircraft: key aspects of aircraft performance (e.g., range) are directly impacted by weight, driving large efforts at weight reduction and therefore optimization of a given component or subsystem against the specific requirements of a given aircraft. Commonality between two or more designs requires one design that meets the needs of the superset of all the models under consideration. Doing so penalizes each design with the exception of a design that contains the maximum settings of all requirements. In the aircraft structure arena, this means that a component such as a strut must be designed to handle the worst case loading conditions. Doing so adds a weight penalty to the less capable models of the family. As a result, structural optimization often proves to be the correct design approach from a total cost of ownership standpoint.

9.2.1. History

Case D examined the history of the most recent in-production aircraft at Company D. The product family consisted of four models, V3.1, V3.2, V3.3, and V3.4 along with their immediate predecessors, V1 and V2. For the purposes of this study, the history was classified into three phases which are illustrated in Figure 97. Phase 1 represents the earliest product models, culminating with development and production of the first business jet within the scope of this study, V1. During this time, the company designed and produced only one aircraft model at any given point in time. New models replaced existing models. Phase 2, consisting of the V2 program, represents a shift from production of a single aircraft model to production of multiple models, the V1 and V2. Phase 3 entailed a shift to development with a product family awareness. The aircraft grouped into Phase 3 are the V3.1, V3.2, V3.3, and V3.4. The three phases are discussed further below.

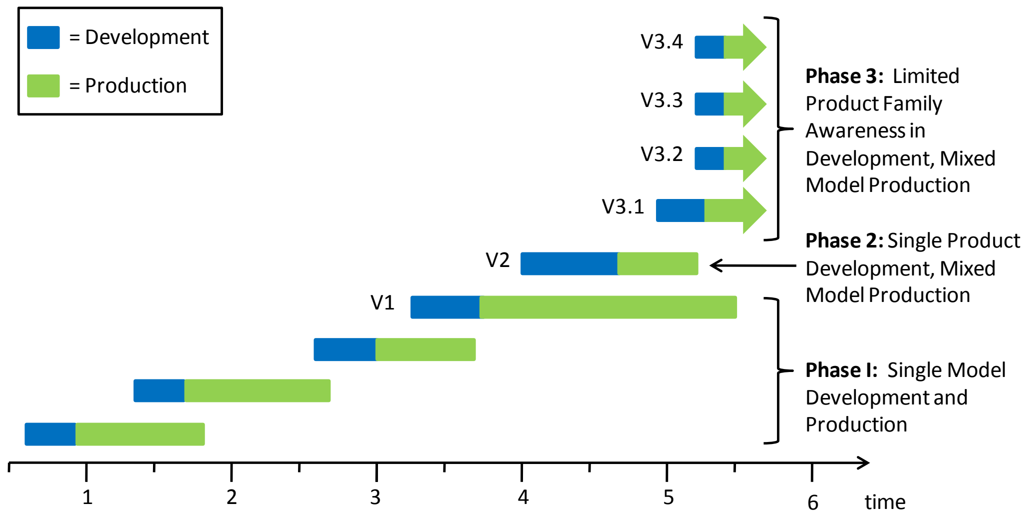

Figure 97: Company D history illustrating the shift from single product development and manufacturing toward multi-product development and manufacturing.

Phase 1: Single Product Model Development and Production

Company D's early history saw development and production of several product models. Only one aircraft was developed at a time and years of separation existed between the introduction of each new model. Each new aircraft program utilized the current generation as a baseline, deviating from the baseline as needed to pursue ever increasing speed, range, and cabin volume. Once developed, the new aircraft replaced the existing design in production, meaning that only one aircraft model was in production at any given time. Replacement was viable because Company D deemed the newer model to be an acceptable offering to the entire business aviation market: the majority of the market desired more performance than was currently available, making retention of a prior model unnecessary. The final aircraft produced in Phase 1 is termed V1 in this study.

Phase 2: Single Product Model Development, Mixed Model Production

The decision to pursue the V2 aircraft started out in line with Company D's history: the V2 was intended to be an incremental improvement beyond the V1, a strategy aligned with the company's historical approach. The V2 would extend the V1 in range by approximately several hundred nautical miles and add cabin volume. The initial concept heavily leveraged the V1 design. The fuselage would be extended by a couple of feet with minor wing modifications utilized to increase fuel capacity and improve aerodynamic efficiency. The engine and cockpit were to be common with the V1.

Several iterations were performed before settling on the V2 concept, with each iteration moving the design further away from the original V1 baseline. Customer feedback on the initial proposal strongly suggested that the range was too limited. The concept was then modified to accommodate significantly increased range, driving the need for a new engine and further increasing the separation between the V2 concept and the prior baseline. A third iteration was triggered by the announcement of a competitive product with a range that exceeded the range of the second round V2 concept. The output of the third iteration was an aircraft with another significant range extension. The concept was now very different from the V1 baseline from the standpoint of direct carryover of parts, subsystems, and manufacturing processes. One interviewee estimated that, at the start of the V2 program, the aircraft was probably 95% common to the V1 but in the end, was probably around 20% common. That said, the design heavily leveraged the basic aircraft architecture; design and construction methods; and manufacturing tooling concepts. While the initial V2 concept had represented an incremental advancement in V1 capabilities, the end output of the design study was an aircraft that served a different market segment. The new V2 could not be considered an effective replacement for the V1, driving the decision to co-produce the V1 and V2.

V2 development followed the same philosophy as in the past: start with the prior baseline and make modifications to meet the envisioned market requirements. No consideration was made of future products in terms of conducting additional design work that may have benefited a future product family. Part of the reason for this was the fact that the V2 was believed to be the last step in increasing capability: the V2 was approaching weight limits at small airports.

During development, the Company D leadership had mandated that the V2 would be produced in the same manufacturing facility as the V1. This drove attempts to share tooling and manufacturing methods where possible. While some common tooling was utilized, the fact that the V1 was in production at the time of V2 development appears to have created similar but mostly parallel manufacturing lines as opposed to true sharing of stations, jigs, fixtures, and processes.

Phase 3: Limited Product Family Awareness in Development, Mixed Model Production
Creation of the V3.1 followed the V2 and represents the first aircraft program that was conducted with beforehand knowledge of mixed-model production. (In other words, the development team knew that the V3.1 would exist in a two aircraft manufacturing environment.) The V3.1 program aimed to make an incremental improvement to the range of the V2 (200 to 300 nautical miles) in order to increase the gap to the nearest competitive product. The V3.1 would be a replacement of the V2.

Following within approximately one year of the V3.1 program was the V3.2, a V1 replacement that was intended to extend V1 range while leveraging the V3.1 improvements to the maximum extent possible. The close spacing of the programs meant that the requirements of both the V3.1 and V3.2 could be considered in parallel with synergies being exploited when possible. One chief engineer was responsible for both programs ensuring high level oversight across the two aircraft programs. Additionally, the design reviews and change control board meetings for the V3.2 involved representation from the V3.1 program.

The greatest synergy across the two programs was probably the common cockpit. The common cockpit effort had been started prior to the V3.1 program. It was folded into both the V3.1 and V3.2 plans and represents the best example of commonality observed during the case study. The common cockpit provides benefits to the customer in terms of reduced pilot training costs and increased pilot flexibility and to Company D in terms of development and recurring cost reductions.

While the close spacing meant that the requirements of both the V3.1 and V3.2 were able to be considered in parallel, the reality was that the V3.1 was Company D's flagship product and would not be compromised for the sake of commonality with the V3.2. As with past programs, the V3.2 program had the option of using preexisting development work but had little direct influence over the outcomes of the V3.1 development work and therefore, the expected utility of V3.1 development to the V3.2 program.

The increase in range for both the V2 and V1 market segments created a market coverage gap that opened the door for competitive products to enter below Company D's two product models. Company D's answer to the market gap concern was the development of the V3.3 and V3.4. The intention was to plug the gap and to do so within minimal investment and lead time. The resulting set of changes created customer differentiated products that have somewhat similar underlying cost structures. Development of the "detuned" V3.3 and V3.4 models was not anticipated during V3.1 and V3.2 development. As a result, the company was faced with the decision of whether to pursue heavy redesign to remove cost or to accept the underlying V3.1 and V3.2 cost structures. The latter choice was selected, with development cost, time, and risk reductions being traded against similar underlying product cost structures. Note that in the case of the V3.3 and V3.4, commonality was extremely high since the models are basically the same aircraft as their more capable cousins. Anticipation of the V3.3 and V3.4 earlier in the V3.1 and V3.2 development cycles may have produced different designs (less commonality across the two pairs) with different underlying cost structures.

Another indication of an increasingly strong product family approach occurred during Phase 3: a standards engineering team was created in order to centralize and standardize completions-related design work. Standardized designs were implemented for interior building blocks such as galleys, lavatories, and smaller components such as lights, handles, and hinges. Additionally, options packages were created in order to reduce the lead time and cost of individual aircraft.

As should be evident from the above discussion, Phase 3 marks a shift in product development strategy: commonality had become increasingly important in the development of aircraft and aircraft features. Although commonality was increasingly important, Phase 3 is characterized as having limited product family awareness because Company D had not fully implemented a platform-based development strategy. Example limitations include the lack of willingness to compromise on the V3.1 design for the sake of future products (i.e., the V3.2) and the lack of planning for the V3.3 and V3.4 during development of the V3.1 and V3.2 products.

9.2.2. Observations

1) **Decades of single product production and replacement combined with long time spans between product releases have created a strong single product culture within the company.** The first several decades of Company D's history were centered on the design and production of increasingly capable aircraft models, with only a single aircraft being produced at any given time. The early product model releases were each separated by time periods ranging from approximately 5 to 15 years. Company D necessarily focused on one model at a time as opposed to the creation and execution of a product family strategy.

Each model started with the current product as a baseline, with modifications being made to meet new requirements. Given the fact that the next model was well into the future, no additional development work was pursued that would potentially reduce the cost, lead time, and risk of a future model.

2) **Reuse is pursued in an informal manner and typically leverages similar, rather than identical, designs, manufacturing processes, and tooling. Potential benefits from direct carryover such as development cost avoidance; realization of economies of scale in manufacturing; elimination of new tooling expense; and a cross-trained manufacturing work force may not be realized.** Reuse, or the use of previously designed parts, subsystems, and manufacturing processes, is engrained in Company D's culture. As with most organizations, reuse was leveraged as much as possible when producing each new model although performance changes between models have driven reuse of the basic aircraft architecture, knowledge, and manufacturing processes rather than direct part carryover.

   Direct carryover has been limited for several reasons. First, the need to produce weight optimized designs combined with new high level requirements (e.g., increased cabin volume or range) results in changes that ripple across the entire aircraft design. Second, the historical single product manufacturing environment returned little in the way of savings based on exact reuse: economies of scale were non-existent in this environment. Learning curve benefits existed but were most likely realized through the use of similar parts. Tooling charges were probably the largest potential savings.

3) **Proactive design for reuse (forward development) in future product models is becoming increasingly important as both the number of product models and development overlap increase.** A product family, rather than a single product, creates opportunities for commonality. As overlap increases in model development, leveraging synergies between programs becomes more beneficial. Additionally, at the level of features, a "design for one model, use across all" philosophy is taking hold in areas such as the cockpit and avionics.

4) **Company D's transition from the production of a single product to two major products (V1 to V1 and V2) combined with increasing overlap in new model development have increased the potential benefits of commonality. These potential benefits have only partially been leveraged.** Company D's decision to add the V2 while retaining the V1 was a departure from the historical single product strategy. This departure was driven by a realization that the continuous move toward increasing capability would leave an unmet need in a lower performance market segment if the V1 was discontinued. Retention of the V1 model while adding the V2 would expand market share rather than shift revenues between segments.

   The single to two product shift changed the potential recurring benefits of commonality. During the single aircraft model production phase, commonality (reuse) presented opportunities for product development cost, lead time, and risk reduction. Manufacturing benefits of reuse included tooling reuse and avoiding the steepest part of the learning curve. With the shift to production of two product models, the potential benefits of commonality increased. In addition to the previous benefits, economies of scale and additional learning curve benefits became potential cost control factors. Production volumes were split three ways: common to both aircraft, V1 only, and V2 only. In effect, the shift increased the potential manufacturing value of commonality. This value can only be accessed by a company producing more than one product.

Company D's single product history, culture, and pre-existing designs, appear to limit its ability to properly evaluate and leverage the potential benefits of commonality, although this is clearly changing. Historical development programs have been challenged in implementing product family approaches. For example, while the V3.2 followed the V3.1 by about one year, the strategy of informal reuse was again prominent: the V3.2 team had the option of using V3.1 components, processes, etc. although the flagship V3.1 was not compromised to enable future commonality with the V3.2 product. Direct carryover was limited. Additionally, the need for the reduced price (and performance) V3.3 and V3.4 was not anticipated during development of the V3.1 and V3.2. A four aircraft strategy most likely would have produced a different outcome in terms of design and the underlying cost structure. More recent development work has begun to more actively pursue a reuse approach: new features are developed with a philosophy of design on one model, deploy on others. Innovations such as avionics improvements are being leveraged across the entire family, resulting in improved customer feature sets across all aircraft and from the Company D perspective, improved development, and recurring cost controls. Additionally, two major improvements have been made in terms of reducing unique work associated with aircraft customization and production: definition of recommended options packages and the creation of a team charged with development of interior strategies and components that offer customers desired uniqueness while maximizing commonality.

5) **Commonality is managed in an informal manner.** While interest in commonality appears to be increasing, the management of commonality is mostly informal.

   - A formal platform manager does not exist for the aircraft family. Ownership occurs at the vice president and senior vice president levels but these executives have a scope of responsibility that extends well beyond managing commonality across aircraft models.
   - Functional managers have strong incentives to pursue commonality to the extent possible in order to reduce their workload and associated costs and risks but these managers have historically supported relatively independent programs.
   - Programs pursue commonality through best effort reuse of an existing aircraft baseline.
   - Change Control Boards have involved people with experience from other programs (e.g., the V3.2 engineering change control board included V3.1 representatives) although inclusions of these employees appears to be based on the desire to access experience rather than for the examination of commonality opportunities.
   - Little evidence of tracking or tagging common parts and processes was found during the study.

6) **Business case analysis has primarily been conducted for individual aircraft programs rather than for an aircraft family.** This mode of analysis does not ensure upfront evaluation of investments in commonality that may benefit future aircraft programs. In other words,

decisions are weighted toward maximizing the value of an individual aircraft program rather than maximizing the value of an aircraft family.

7) **Company D's approach to commonality has been to identify common features that provide direct benefits to the customer. Company D's strong customer focus has deemphasized potential internal benefits of commonality although this perspective appears to be changing.** The pursuit of commonality across aircraft models has been aligned with Company D's strong customer focus. Examples include the common cockpit and avionics options. Additionally, standardization of interior options such as galley and lavatory forms has created a constant look and feel across models. In cases where the customer is interested in commonality, both Company D and its customers see benefits. Outside of commonality opportunities that provide direct benefit to the customer, pursuit of commonality (i.e., exact part number or manufacturing process carryover) has been limited by the single product history of the company.

9.3. Case E: Printing Presses (Commercial)

9.3.1. Introduction

Company E is a manufacturer of industrial printing systems. Company E's customer base has traditionally consisted of small printing shops with one printing press, although the installed base is rapidly transitioning to companies that operate more than one press. Customers operating two or more presses are considered to be "large" and few customers operate more than four presses. Given the relatively large number of customers (a few thousand) and small number of units sold to each customer (most often one or two units), Company E avoids allowing large customers to sway product designs too significantly. Product goals focus more on the aggregate needs of a market segment than the needs of one or a small handful of customers.

Company E generates revenues from the sale of its printing presses (approximately 50% of revenue) and through the sale of consumables utilized in press operations and support (50% of revenue, combined). Unlike the one-time revenue generated from the sale of a product, supplies and service generate a continuous revenue stream throughout the life of a given product, which is assumed to be about 5 years. Lifecycle revenues from supplies such as inks are important to the bottom line.

Company E's printing press portfolio consists of three product lines. Product Line 1 ("PL1") systems print on sheets of paper. Product Line 2 ("PL2") systems print on rolls of alternative materials. Product Line 3 ("PL3") systems print on rolls of paper.

Company E's approach to new product development has been centered around development of a new core printing technology, followed by deployment of this technology into multiple market segments in order to leverage the initial investment and the cost, lead time, and risk benefits of reuse. The company heavily leverages its printing technology, software, and control system components, all of which represent large investments. Given that volumes are highest in Product Line 1, this line typically serves as the lead variant for a new printing technology, software system, or major new feature. The other two product lines then combine the applicable Product Line 1 innovations with Product Line 2 specific or Product Line 3 specific advancements to address the needs of the other market segments.

The Company E printing press product history, as discussed here, is focused on those products that have been derived from a common printing technology, although prior products are discussed briefly. The history discussion is organized around the following five topics: Pre-Product Family E History; Product Family E Lead Variant; Product Line 1 Derivatives; Product Line 3 Derivatives[58]; and Product Line 2 Derivatives. The purpose of the history section is to present enough historical information to motivate the later discussion of case study observations, rather than to provide an in-depth history of detailed changes. Figure 98 illustrates the products included within the Product Family E history.

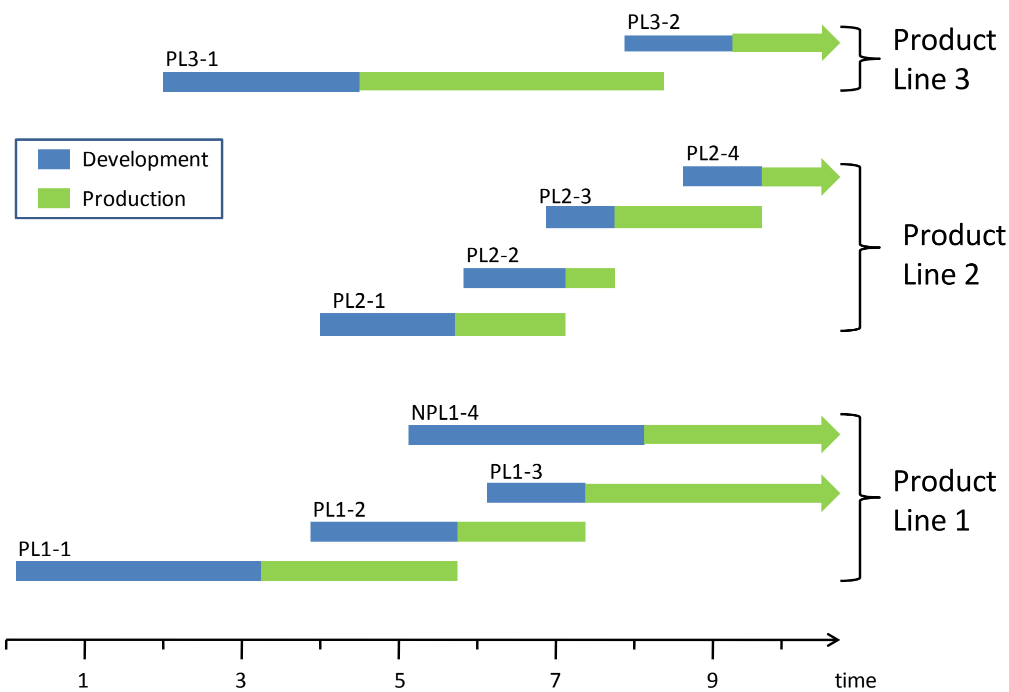

Figure 98: Product Family E history. Bars represent approximate development start, first shipment, and last shipment. Within a given segment (e.g., Product Line 1), new models replace prior models with the one exception being overlap between the PL1-3 and NPL1-4 models.

9.3.2. Brief History

Pre-Product Family E History

While the products Company E sold prior to Product Family E were not the primary focus of this study, it is important to note two aspects of this prior history. First, prior to development of the core Product Family E printing technology, Company E had significant printing experience, as evidenced by the company's prior product history. Second, the prior product history

[58] The Product Line 3 discussion is presented first due to development order. The original naming convention utilized in the study was based on relative product importance (sales volume).

illustrates the experience Company E had with developing replacement models for existing products and in expanding its product line to address new market segments. The former experience entailed incorporation of learning from prior generations and technological advancements to create improved products. The latter entailed leveraging existing technologies to exploit new market opportunities.

Two years prior to developing the first member of Product Family E, the team began development for a new printing technology. The technology development effort was aimed at doubling the printing speed of the current products, with the initial intention being to literally speed up operation of the existing hardware. The technology development team quickly demonstrated promising results that were worthy of commercialization: the improved printing technology had the potential for printing rates that were two to three times faster than its predecessor, but the required changes to the underlying printing elements were more significant than initially anticipated.

Product Family E Lead Variant: PL1-1

The goals of the PL1-1 development program were to increase productivity; reduce cost; and maintain or improve upon output quality in comparison to prior product models. These goals would be achieved through the use of the still-in-development core printing technology and through addressing issues and improvements uncovered by production and operation of Company E's previous products (Figure 99).

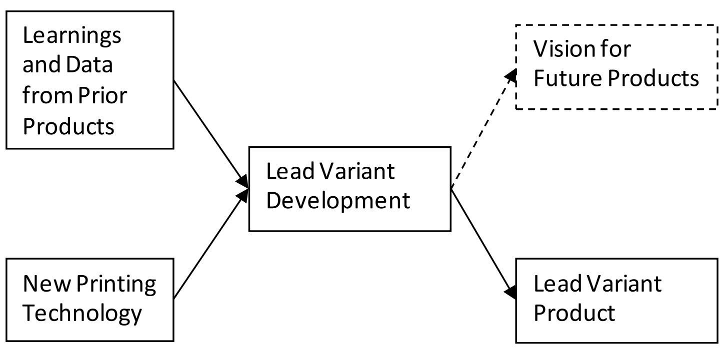

Figure 99: The lead variant (PL1-1) program addressed learning from prior products while utilizing a new technology building block to increase productivity.

Development of the new printing technology and the PL1-1 product were very large efforts and created a large strain on the company's resources. Early in the development program, a key executive had mandated that as little as possible would be changed between the prior product and the PL1-1. The push for reuse simply made sense given the resource limitations. The initial vision of limited change did not materialize, but reuse was only a strategy for meeting market needs in a cost effective manner rather than an end objective. The primary goal was obviously the creation of an effective product, not reuse. In the end, one interviewee estimated that roughly 80% of the prior product was modified to produce the new model.

While PL1-1 was a single product, a vision existed for the creation of a series of products that were based on the same printing technology. After addressing the largest market opportunity, the segment addressed by Product Line 1, the printing technology would be expanded into the other two market segments. This approach would ensure that the initial technology investment was leveraged to the maximum extent possible. During development of the original PL1-1 product, plans existed for three follow-on variants:

- **PL1-1.1:** a single printing system with duplex capabilities and the ability to handle a wider range of materials
- **PL1-1.2:** two integrated systems with duplex capability
- **PL1-1.3:** four integrated systems with duplex capability and roll substrate capability

While the final products in the family changed, the development team was clearly thinking about future models during the development of the lead variant. The PL1-1 product development effort had laid a foundation for the remaining product family members as is discussed below. The PL1-1 product was successful in the market.

The Product Line 1 Derivatives: PL1-2, PL1-3, and NPL1-4

The PL1-1 product was a major new product for Company E and as with many new products, a significant amount of learning occurred during development, manufacturing, and field operations. The team addressed issues associated with the PL1-1 product through two follow-on derivatives, the PL1-2 and PL1-3. The first revision, the PL1-2 was aimed at improving paper handling reliability (reducing the number of paper jams). The second revision, the PL1-3, addressed a list of issues identified through field operation of the original PL1-1. Important to note is the fact that both the PL1-2 and PL1-3 programs were primarily focused on fixing existing product issues, as opposed to enabling new features or future products.

The next Product Line 1 product, NPL1-4, extended product capabilities significantly. The program aimed to improve customer ease of use, reliability, and the overall customer experience, while also providing a dramatic cost reduction in comparison to the PL1-3 baseline. While the basic printing technology was retained with minor modifications, much of the rest of the system was changed to meet the new requirements.[59] The entire paper handling system was new and was intended to be new from the beginning of the program. The control electronics were near the end of their useful lives and needed to be replaced. During the redesign process, the control system architecture was changed from centralized to distributed control. These changes drove the need for all new software. While the control system and software architecture changes were intended from the beginning, the required investment was higher than anticipated (roughly 3.3 times the investment in the original Product Family E model), due to both development complexity and internal organizational changes that drove inefficiencies in development. The overall system architecture was redesigned to enable mixed model manufacturing of the NPL1-4 and its future derivatives, a first for Company E. Even the industrial design aspects of the product were redone in order to create a new look and feel for the product. The end goal was to create a revised platform that would leverage the existing printing technology and serve as a foundation for future derivatives for several more years.

[59] The NPL1-4 was included in the study because it leverages the core printing technology associated with Product Family E; however, from a hardware and software standpoint, the product represents a new platform.

As with most product development programs, the vision for the NPL1-4 product evolved throughout the course of development. During the formative phase of the program plan (circa one year prior to the "official" development start), the goal was to create a product that could be manufactured for about 75% of the PL1-3 cost; to halve the PL1-3's cost per page (variable printing cost); and to improve factors such as reliability and ease of use. At program kickoff, the cost reduction emphasis continued along with the need to improve ease of use and to provide a slight enhancement to the feature set. As the development effort continued, it became clear that the program team would not be able to deliver on the entire initial vision: the program scope had to be reduced. The original change "axes" were retained but the weighting between them was changed. The main focus became bill of materials cost reduction and ease of use improvements with the intent to also provide a minor reduction in cost per page.

Similar to the PL1-1 product, the NPL1-4 was viewed as being the lead variant in a next-generation product family. Early in the planning cycle, the team knew that it wanted to base future derivatives on the NPL1-4 platform, mostly around the paper handling system, software, and controls. Two derivatives were envisioned but little to no analysis was conducted in support of this vision and its associated business case. No explicit steps were taken during NPL1-4 design to ensure that the two follow-on variants could be easily created with the NPL1-4 program outputs.

Mid-way through the NPL1-4 program, management initiated a program aimed at developing the first variant configuration of the NPL1-4 that would enable high efficiency duplex printing. This program was placed under the NPL1-4 program manager and resulted in two development programs that were running in parallel with offset starts. The derivative program was ended after about one year because it was slowing down the lead program and consuming too many resources. Additionally, it appears that the product may have had limited market value given that it only had a benefit for duplex operations.

While development of NPL1-4 was a challenge, the program has been highly successful from the standpoint of market acceptance. The initial program plan for improved ease of use and reliability has materialized and has been rewarded with strong market success. As of the end of 2006, the NPL1-4 had sold more units than any other product in Company E's history. Upon release, the cost reduction over the PL1-3 was about 10% rather than the goal of 25%, but this reduction combined with increased price has contributed to substantial margin improvements. These margins have combined with high volumes to produce very strong profits for the company.

The Product Line 3 Derivatives: Demos, PL3-1, and PL3-2
The products described above, represent the largest portion of Company E's revenue and serve as the foundation for other products, both for paper and for alternative materials. The initial Product Line 1 investments were leveraged for other product lines to increase product development efficiency.

The origin of the Product Line 3 machines was a complex technology demonstration system that was intended to basically combine four PL1-1 cores with a new handling system for rolls of paper. Significant architectural differences existed between the sheet and roll processing systems due to the need to process a continuous roll of paper. The entire paper handling system had to be redesigned to accommodate the handling of a roll of paper rather than individual sheets and the underlying printing process had to be modified to accommodate roll paper operations.

A modular approach was taken to simplify development; to support outsourcing of the paper handling system; and to enable future scaling for one, two, and four printing cores in the spirit of the original PL1-1 vision. The entire paper handling system design was outsourced and designed to fit between the printing press walls. Doing so decoupled development of the paper handling system from the rest of the system. As an additional example, the control system was designed in a master/slave configuration; allowing the team to link the four PL1-1 printing press controllers with minimal data transfer between the presses, and therefore, across the overall system.

The complexity of the demonstration unit combined with near-term delivery commitments led the company to scale back its design to leverage two press cores. The commercialized version became the PL3-1 and after incremental advancements, the PL3-2. Sales volumes of the Product Line 3 derivatives are low relative to the other product lines and tend to require customization. For these reasons, little attempt has been made to maintain commonality between Product Line 3 and the other product lines.

The Product Line 2 Derivatives: PL2-1, PL2-2, PL2-3, and PL2-4

The Product Line 2 machines allow customers to process rolls of alternative materials. The need to process continuous rolls of materials means the products have similar printing process constraints to those addressed by Product Line 3.

PL2-1: The initial Product Line 2 product, the PL2-1, followed development of the first Product Line 3 product, PL3-1. The original plan was to use the PL1-1 printing core and the Product Line 3 demonstration system paper handling mechanism as design baselines and to make modifications as required. The two programs (PL2-1 and PL3-1) had separate program managers but shared a common substrate handling group, ensuring strong coordination in this area of development. The two programs had different requirements that impacted their design decisions in different ways. The Product Line 3 products were the result of a technology demo-turned-product that was under intense schedule pressure. The PL2-1, on the other hand, was not as constrained by schedule but faced more stringent performance requirements.

Several key successes were achieved with the PL2-1 product. First, the basic printing technology had been reused. Second, one configurable version of software was utilized for both presses.

While the vision for combining the PL1-1 printing technology with the PL3-1 substrate handling system was simple, many design modifications had to be made to accommodate the more stringent requirements of the PL2-1 and the shift to alternative materials. The team made many modifications to the baseline designs. For example, the substrate handling mechanism had to be modified for single printing core operations and to meet more stringent operational requirements. Also, the electrical cabinets were modified to remove unnecessary cost and footprint, given reduced electrical requirements. The PL2-1 development program also required the addition of several new features that were not developed for the PL3-1. Other features were deleted; e.g., the second printing press core and paper inverter.

As the above summary demonstrates, the PL2-1 program represented a typical product development program. A baseline was identified. New features were added to the baseline to meet the new market requirements and unnecessary features were subtracted. The baseline was modified as required to accommodate feature addition and subtraction and to meet the new market requirements. The PL2-1 addressed a different set of requirements in comparison to a strictly more or less stringent set of requirements.

PL2-2: PL2-2 was an incremental product advancement that incorporated several features that were not within the original PL2-1 scope and addressed initial inputs gained from field operations.

PL2-3: The next product in Product Line 2, the PL2-3, was focused on increasing PL2-2 market share by increasing the types of substrates that could be printed. The PL2-3 program incorporated improvements, such as improved color control (software), from the latest Product Line 1 product (the PL1-3), enabling Product Line 2 to access new features that could not have been developed based solely on Product Line 2 revenues. The Product Line 2 revenues and profits alone did not justify the investment. It is important to note that the PL2-3 program was selecting improvements from the existing PL1-3 design, a design that had been created with the sole focus of making improvements to Product Line 1. The PL1-3 and PL2-3 programs had not collaborated to determine the best design for a feature, given the feature's use across multiple products.

While some of the PL2-3 developments had the potential to be transferred into other product designs, there was never any mandate for commonality between the PL2-3 program and the other programs. As was the case with other programs such as the PL1-3 development effort, the PL2-3 program did not conduct any forward-looking development to reduce future program costs; increase future product performance; etc. The purpose of the PL2-3 program was to bring the Product Line 2 product closer to the needs of its market segment, not to develop new building blocks for future products.

PL2-4: The primary goal of the PL2-4 program was to increase press throughput in comparison to the PL2-3, a difficult task given that throughput improvements are very difficult to achieve without modifying the underlying platform (e.g., the printing core and substrate handler). The team ultimately focused on understanding and reducing overhead reductions associated with press operations. Time studies were conducted at customer sites in order to understand how operators spent their time and to identify design improvements where possible.

The most significant design change associated with the PL2-4 program was the incorporation of the NPL1-4 ink cabinet. This change increased press utilization by enabling inactive inks to be changed during printing operations. Reliability was also improved. Integration of the new ink cabinet with the existing PL2-3 baseline was very challenging due to underlying differences in the PL2-3 and NPL1-4 control systems: the PL2-3 has one master CPU, while the NPL1-4 has a highly distributed control system. Development of this feature was at least partially collaborative as test results were shared between Product Line 1 and Product Line 2.

Additional Comments on Commonality between Product Lines 2 and 3

There appear to have been three main reasons for a reduction in commonality between Product Lines 2 and 3. First, the initial PL3-1 was designed for one specific customer that had placed firm orders. The team developed a customized machine for these specific orders. The team had little interest in (or time for) anything else. Second, Product Line 2 requires greater accuracies and must handle alternative materials that are more difficult to process. These more stringent requirements did not make sense for the PL3-1 as they would have driven unnecessary design changes and cost increases. Third, at the time of PL2-1 and PL3-1 development, there were no follow-on PL3-1 orders. Given the lack of orders, there was no reason to retrofit PL2-1 improvements back into the PL3-1 design. This approach minimized development effort and risk for the PL3-1 while avoiding the creation of artificial constraints that may have impacted the PL2-1 product's ability to meet the needs of its own market.

9.3.3. Product Data Analysis

An extensive Bill of Material data analysis was conducted as part of this case study. The Commonality Analysis Tool was utilized to examine commonality (sharing and reuse) across the product lines. Several key analysis outputs have been included here. The analyses reported in this summary report are based on unique part item counts rather than part costs. All parts costing less than $5 were removed to avoid masking trends with low cost items such as fasteners. The true connection to cost is by analogy. While cost analyses were also conducted, data structure limitations limited my confidence in the outputs.

Figure 100 illustrates the evolution of commonality (sharing) levels throughout the product family history. As time has progressed, the total number of parts has increased due to the addition of new products and increasing product complexity. Between Period 11 and Period 30, the number of common elements (defined as being common to any two or more product lines) has decreased by about 14% while the total number of parts has increased by 84%: the relative reduction in commonality is much more significant than the absolute reduction. Figure 100 also illustrates the large impact of the introduction of major new models, such as PL1-1 and NPL1-4. Introduction of new minor models such as the PL1-3 and PL2-3 did not have a large impact on part count distributions, supporting interview comments regarding the incremental nature of follow-on products in a given product line.

In addition to the full family analysis, two simplified views were created to further investigate interesting points from the interviews. A comparison was made between Product Lines 2 and 3. Based on the interviews, the original PL2-1 and PL3-1 were developed mostly in parallel and were intended to share the same basic printing core and substrate handling mechanism. The PL3-1 led PL2-1 development slightly and the intention was to heavily leverage PL3-1 developments in the PL2-1 development effort. The interviews also suggested that the initial intention of high commonality was relaxed with time for a number of reasons. As identified in both the interviews and data analysis, commonality reduced with time (Figure 101).

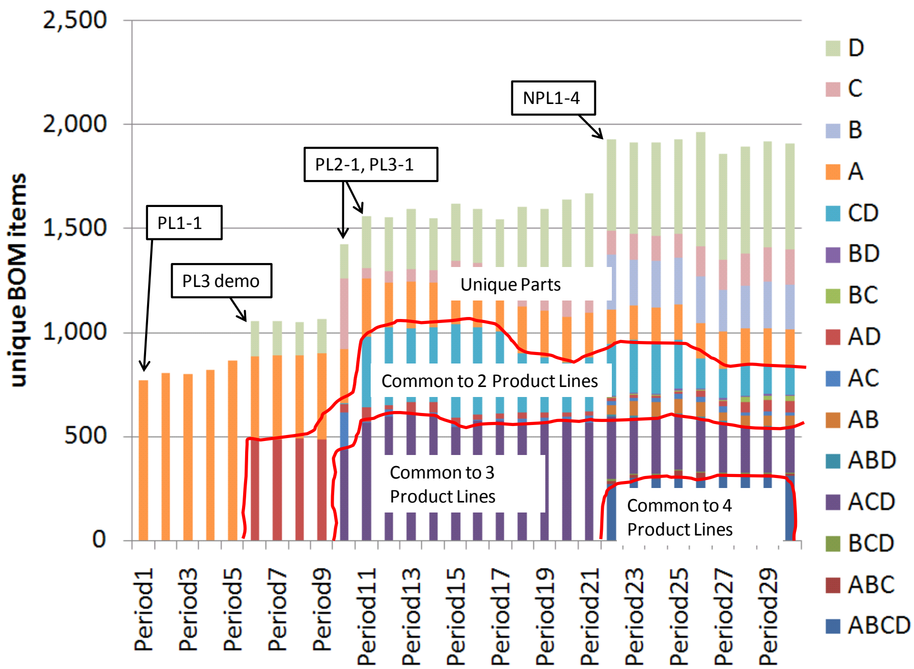

Figure 100: Part sharing analysis illustrates unique parts and parts common to two, three, and all four product lines. Legend letters correspond to Product Line 1 ("A"), NPL1-4 ("B"), Product Line 2 ("C"), and Product Line 3 ("D"). (Parts costing less than $5 were removed. Red lines are inexact: for illustration purposes only.)

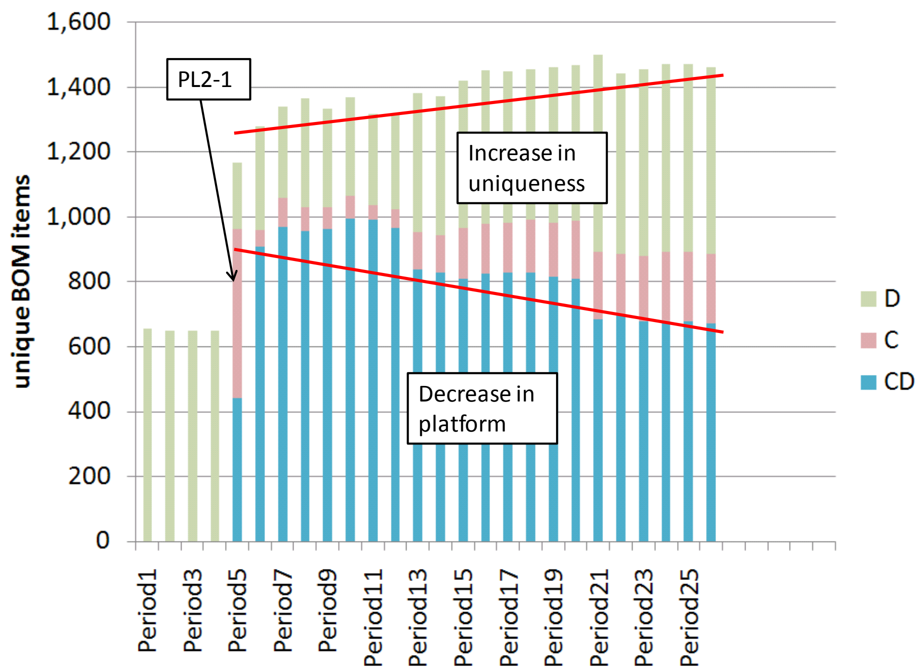

Figure 101: Sharing analysis between Product Line 2 ("C") and Product Line 3 ("D"). Common parts have reduced with time while the numbers of unique parts and total parts have both increased. (Period 1 corresponds to the start of PL3-1 production. Parts costing less than $5 were removed. Red lines are inexact.)

The reuse portion of the analysis consisted of determining the original source of each part (time period and whether from within the product line or from one of the other product lines). Doing so provided insight into three areas. First, the overall degree of change within each product line was identified. Changes represent potential opportunities for lost commonality. Second, the product line's incorporation of components developed or sourced within other product lines was determined. This category represents leveraged investments from prior development efforts. Third, new development within the product model was determined.

Reuse analyses based on unique line items are included in this summary report for Product Line 1 (PL1-1, PL1-2, and PL1-3) and Product Line 2 (Figure 102 and Figure 103, respectively). Even though Product Line 1 is viewed as the lead product line, the analysis suggests that all product lines have benefited from carryover from other product lines. Product Line 1 has leveraged other products the least, supporting the fact that the Product Line 1 products are typically the lead variants in development. The following two figures are interpreted as follows:

- The leftmost column represents the first bill of material available for a given product. This column either has one or two sections. The top (or only) section represents new development for the product under analysis. The lower section (if present) represents carryover from other products that existed in the prior period. By definition, the PL1-1 product had no reuse from other product lines because it was the earliest product within the scope of this study. While the PL1-1 product almost certainly reused components from earlier products, these products were not included in the study.
- At each time period, two new column sections are potentially added. A new section above the upper red line in the charts means that new development occurred within the current product line at the current time period, i.e., the parts did not exist at the previous time period. A new section below the lower red line in the figures represents incorporation of existing parts (new to the product line under study) that were developed in another product line at any time prior to the current period; i.e., reuse.
- Existing column sections can only reduce in size with time. Reductions signify replacement of components and rates of reduction indicate the degree of churn in the product line.

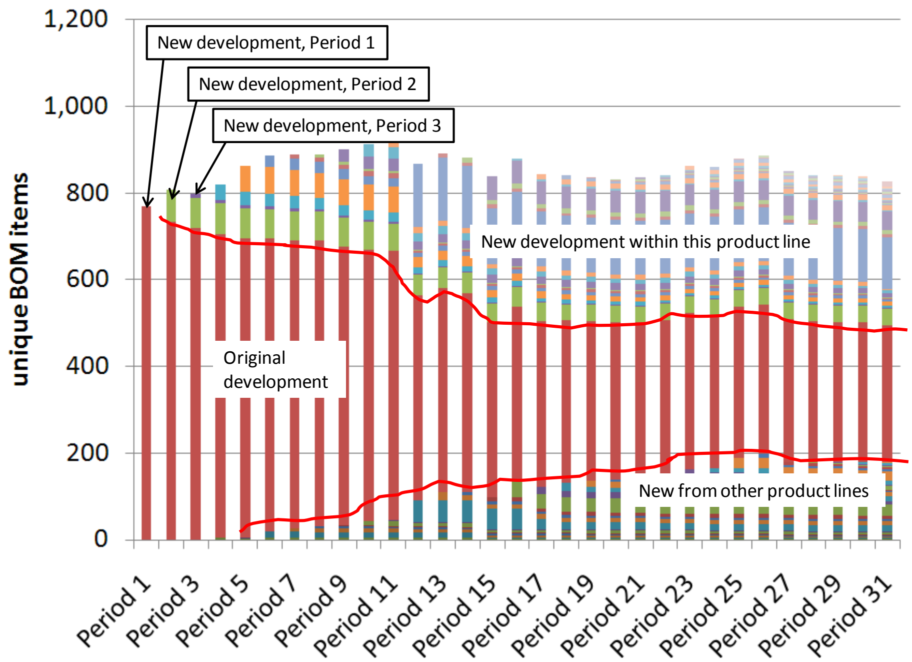

Figure 102: Reuse history for the Product Line 1 products (PL1-1, PL1-2, PL1-3; NPL1-4 excluded) shows a typical product history trend. New components are inserted through within-product-line development (above upper red line) and through carryover from other product lines (below lower red line). (Parts costing less than $5 were removed. Red lines are inexact: for illustration purposes only.)

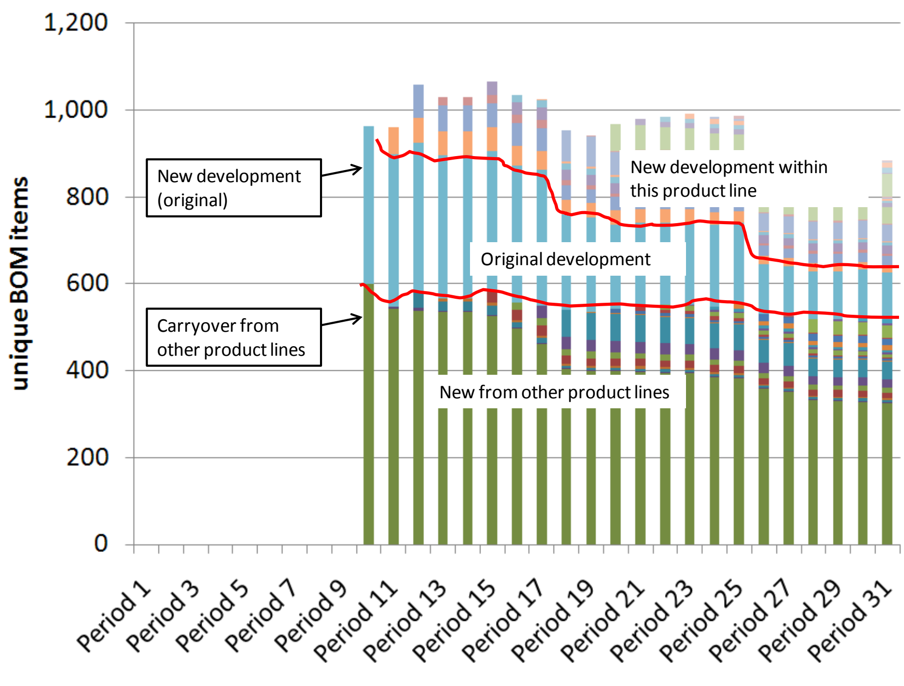

Figure 103: Product Line 2 part reuse. The number of parts sourced from other product lines is relatively constant (below lower red line). While the extent of reuse is only slightly decreasing, significant churn exists in these components as evidenced by the multiple color bars below the lowest red line. Also note the high degree of churn that has almost completely replaced the originally developed components (light blue). (Parts costing less than $5 were removed. Red lines are inexact: for illustration purposes only.)

9.3.4. Observations

1) **Company E has heavily leveraged platform investments, as evidenced by the large investment in the first Product Family E product, followed by derivative product investments of less than 15% of the lead product investment.** While this study could not determine the degree to which the investment in the first product and underlying printing technology was efficiently utilized, follow-on product investments are an order of magnitude lower with the exception of the PL3-1 investment (Figure 104). Clearly, Company E has utilized its initial platform and technology investments across a family of products that reach the three addressed market segments.

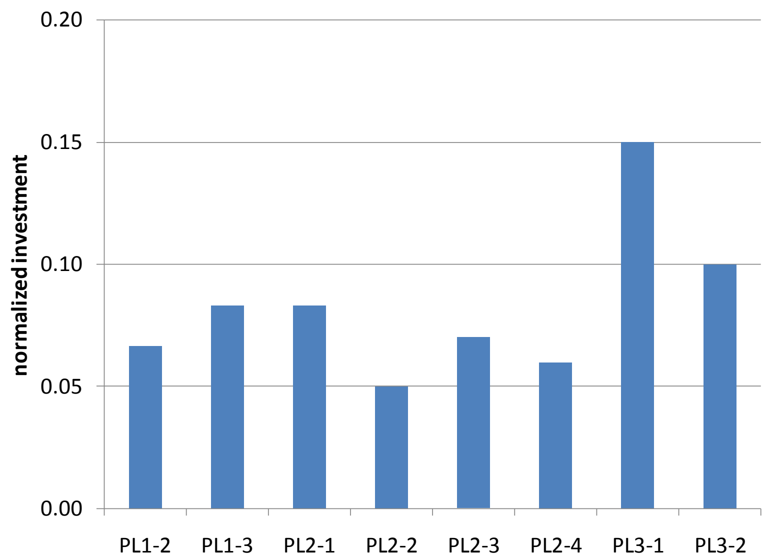

Figure 104: Normalized investments for Product Family E products, less NPL1-4. Maximum follow-on derivative investment (15% of lead variant) was for PL3-1. All other products have been at or below 10% of the initial investment.

2) **Company E's products contain a high degree of reuse from prior generations. Reuse controls program costs, lead times, and risks. Reuse is critical to efficient resource utilization and to providing rapid incremental advancements prevalent within the high tech sector.** Reuse is a natural approach to product development and is engrained in Company E's corporate culture, as in many other corporate cultures. All products tend to start with the prior product model as a baseline. For each product development program, new product needs are understood; existing building blocks are surveyed for applicability to the current development program; and then the building blocks are modified accordingly.

3) **Reuse is "reactive" rather than "proactive."** Product development programs have the option to reuse previously designed modules that were created with the needs of the prior product in mind. Product development programs do not intentionally pursue building block development that would reduce the costs, lead times, and risks associated with follow-on product models.

4) **The scope of product development efforts typically increases with time, effectively reducing the degree of direct reuse between a new product and its previous generation.** Products that were intended to be minor modifications often resulted in much larger amounts of change in comparison to that which was initially anticipated. The most significant example of this trend is probably the original plan for the underlying technology and resulting lead product which was intended to be a "quickened" version of the prior generation product. The end result was a nearly complete redesign.

5) **Due to significant differences in product demand and revenue, Company E leads with Product Line 1 (high sales volume) product development and later transfers new product features to the lower volume product lines. Commonality enables the lower volume product lines to access new features and development work that could not be justified for either lower volume program.** In terms of sales volumes, more than five Product Line 1 systems are sold for every one Product Line 2 system, with few Product Line 3 products being sold. While product prices vary, the relative importance of the three product lines is aligned with their sales volumes. The large offsets in product volume and revenue have led Company E to make its major development investments in Product Line 1, primarily PL1-1. The high revenues justify much larger development investments than could be justified for the lower revenue products. Product Lines 2 and 3 leverage applicable new developments from Product Line 1, while focusing their program investments on the unique aspects of their individual market segments.

6) **A direct tension often exists between advancement (e.g., innovation and incorporation of field learnings) and commonality, which equates to reuse in a sequential product development environment. The rapid pace of technological advancement exacerbates this trend.** The tension between innovation and commonality (reuse) was obvious to many of the interviewees. Learning is generated from fielded products; technologies are advancing; and new customer needs arise. In a leader-follower development environment such as Company E's, these changes erode commonality: alignment between products can only be maintained if in-production products are upgraded. The business case for making changes to existing products is often less than compelling due to the high costs of changing existing products and the incremental benefits of maintaining commonality.

7) **Company E has historically developed product family visions, but these visions were not strongly coupled to a product family business case analysis and to explicit design actions aimed at easing development of future variants. The development of a product family vision was followed by relatively independent development of each product model, resulting in only partial realization of the benefits of a platform-based product family.** The desire to leverage core technologies and system elements such as the core printing technology, software, and control system has led to the formation of early product family visions. As an example, the Product Family E vision existed early in the development of the lead product, PL1-1. An early program document clearly described the vision for scaling the original platform in several directions. Three models were planned beyond the initial product. While the number and type of planned products changed with time, important for this discussion is the fact that derivative programs proceeded in a relatively independent manner.

An additional example of a product family vision can be found within the newer NPL1-4 program. The NPL1-4 had two initially planned follow-on variants. While a product family vision existed, little definition of the products occurred until development of the first follow-on variant was started approximately halfway through development of the NPL1-4. Development work on the first follow-on variant represents the strongest example of coupled, parallel development of two products identified during this case, although this program was cancelled due primarily to delays induced by resource limitations.

Product Family E has clearly leveraged core technologies and many similar components and subassemblies. What has been missed were opportunities for exact commonality that may have provided additional development cost, lead time, and risk reductions through direct reuse; recurring costs reductions through economies of scale; and cost benefits in operations. Company E is moving toward increased coupling in the development of its product families and increased leveraging of commonality across these products. Examples include the strong attempt at common development for the NPL1-4 and its derivative and the use of "Vintage Charts," which are formal product family roadmaps created through the analysis of market needs, research and development capabilities, and program economics.

8) **Lead variant ownership of commonality creates a "fox guarding the hen house" situation. Product development decisions are made in the best interest of the lead variant rather than in the best interests of the product family. For example, delays of the lead program are not accepted for the sake of product family development.** The lead variant program manager is incentivized to meet the goals of his or her product, not the goals of the larger product family. Development schedules, budgets, and risk tolerances are all very tight, driving program managers to avoid scope increases beyond what is required to meet the needs of their current program. The result is product level "optimization" rather than optimization of the product family. The latter is better-aligned with overall corporate profitability goals.

9) **The main platform emphasis is on the reuse of technology (e.g., printing process technology), rather than the direct carryover of parts and modules. Limited commonality at the part and module levels (i.e., same part number) likely reduces the engineering design, manufacturing, and operations benefits.**

10) **The core printing technology is heavily leveraged across a family of products (e.g., Product Family E) due to high development costs, lead times, and risks. The printing technology and common supplies, such as inks, represent core platform elements.** Development of a new printing technology entails extremely large investments. The Product Family E technology and lead variant were very expensive to develop, while each follow-on program cost on the order of 15% of this cost or less. The large platform investments are amortized across a series of related products through adaptation of the associated technologies and parts to the needs of each market segment. Supplies such as inks and rolls are tightly coupled with printing performance and are kept as common as possible for this reason. In addition, commonality in supplies has significant operational benefits from the standpoint of Company E and its customers.

11) **The core printing elements represent a process technology and related functions rather than a well-defined module with clearly defined interfaces. The tight integration between the core printing components and the rest of the product reduces commonality because changes are required for adaptation of the core printing components to each product model. The result is reduced commonality at the part level and an inability to manufacture core printing modules on a common line, even though similarity across products is high.**

12) **The software and control system represents a second key platform element. Like the core printing components, software and control system elements represent large investments that are leveraged across a series of products.**

13) **Product development programs, their management, and the overall corporate culture focus heavily on the development of individual products. Coupling between programs has been limited and even rejected in some cases. Interviews suggested that multi-product approaches to product development may be becoming more prevalent.** Company E's culture and management style is strongly focused on the creation of individual products. While reuse from prior generations occurs, each program is focused on meeting the needs of its individual market segment as opposed to the creation of building blocks that will be used across multiple future products. Program managers' goals are tied to the performance of their individual products, driving scope minimization to reduce near term development costs, lead times, and risks. Program managers feel pursuing commonality beyond simple reuse delays their programs or limits product performance in some manner; both of which are compromises that they are unwilling to accept.

    The interviews suggested that a shift from independent program to multi-program thinking may be occurring, although results are mixed. As Company E and its addressed markets mature, an increasing emphasis is being placed on underlying product cost structures. Mixed-model manufacturing is being pursued, a strategy that depends on commonality and similarity in order to reduce inventories and to leverage economies of scale. Interest may be moving toward parallel, coupled development of multiple products, although a recent attempt (development of NPL1-4 and a follow-on variant) was unsuccessful.

14) **Product commonality is managed informally. Neither dedicated multi-program development managers nor an overall owner of commonality were identified. One example of a formal management process was identified, the Program Coordination Meeting.** A formal manager of commonality across product lines was not identified. The default owners of commonality are the management team. The Research and Development and Product Engineering Managers are interested in commonality but have very broad responsibilities. Their ability to develop commonality strategies and manage commonality across product lifecycles is limited due to their other responsibilities. Program managers all focus on individual products, with the exception being the previously discussed NPL1-4 and derivative that were both placed under the same program manager. This study identified one formal commonality management mechanism: changes to product models and their associated costs are presented during the Program Coordination Meeting and must be

approved by all program managers prior to implementation. No additional formal controls were identified.

15) **Common and/or similar parts are not tracked, measured, or reported.** Commonality is not tracked across different product lines nor across generations of a given product line. Opinions of commonality levels varied widely within the organization. Qualitative estimates tend to be the highest in the process side of Research and Development (process commonality is high) and lowest from the perspective of Manufacturing (exact part commonality is lower).

16) **Analysis of the lifecycle benefits and penalties of commonality (i.e., the business case for commonality), is limited, although there is a strong awareness within the organization about the need for commonality in certain critical areas, such as printing technology, inks, and other supplies.** No evidence was detected of formal business case analyses that extended beyond more than one product. The organization clearly considers the benefits and penalties of commonality but does not attempt to quantify them. A strong qualitative awareness of the lifecycle cost impacts of common versus unique parts and supplies exists due to the high percentage of revenues (approximately 50%) that are attained from supplies and service. Formalized lifecycle analyses and trades were not identified during the interviews.

17) **The perceived benefits and penalties of commonality, along with the definitions of commonality vary across the organization.** For example, Research and Development benefits from basic process carryover, and therefore emphasizes this aspect of commonality. From the perspective of process R&D, the product family members are highly common. At the other end of the spectrum is Manufacturing, which tends to define commonality based on part number designations. Manufacturing complexity is partially driven by the number of unique part numbers associated with each product. Common part numbers enable common assembly and test and reduced inventories. Similar parts may still provide assembly and test benefits but inventory benefits are lost. Manufacturing tends to feel the products are much less common, due to the organization’s more detailed perspective.

18) **The importance of commonality is increasing as Company E focuses more on the underlying cost structure of its products and as the customer base shifts from single product operators to multi-product operators.** As the industry matures, competition can be expected to increase. Reducing differentiation between products will increase margin pressures and drive internal scrutiny of underlying product costs. Commonality represents one potential path to cost control. Company E appears to be exploring this avenue in greater depth as evidenced by a move to mixed-model manufacturing, for example. The shift from single press operators towards multi-press operators emphasizes commonality from the customer side. Examples of factors that may be important to a multi-press operator include commonality in press operation, service, supplies, and spares.

19) **Learning from the production, operation, and servicing of existing products drives improvements in future products and often causes divergence, or the loss of commonality, in the existing product family. The cost of implementing improvements in a**

new design is very low, while the cost of retrofitting existing designs is much higher, often high enough that the cost outweighs any expected returns. Improvements based on prior product history can easily be incorporated into new product models because the cost of implementing a change is very low. Incorporation of fixes into existing product models, outside those that are critical to safety or to meeting promised specifications, is less likely, as the cost of modification is much higher. The result: field-generated knowledge drives advancement of new products and divergence, or the loss of commonality over time, within the entire product line.

9.4. Case F: Communications Satellites

9.4.1. Introduction

The communications satellite industry has traditionally utilized large, highly capable satellites. Company F has taken a different approach by offering a smaller, less capable satellite that reduces per satellite costs. The smaller satellite capacity and associated reduction in acquisition cost (approximately 50%) enables customers to make smaller incremental investments in capacity, thereby improving a satellite operator's match between market needs and available capacity. In addition to enabling smaller incremental expansions, Company F is able to deliver satellites at competitive lead times that are attractive to satellite operators from the standpoint of better capacity matching and earlier revenue recognition.

As is the case with other satellite providers, a key element of Company F's strategy is the utilization of a bus/payload approach that is intended to maximize carryover across satellite programs while ensuring each customer obtains the required communications performance. The Company F bus provides non-differentiating functions such as propulsion, attitude control, supporting structure and thermal management. While these basic functions are common across every communications satellite, the detailed performance specifications are certainly not. For example, power requirements change depending on the number and type of communications channels supported by the satellite. Successful implementation of the bus strategy requires a thorough understanding of the full market requirements envelope and the discipline and resources to design to this envelope. Inability to do so results in a high degree of design churn in the bus and a reduction in the benefits of the bus approach.

Unlike the supporting functions provided by the bus, the payload provides the direct communications functionality that creates value for the customer. Communications payloads are highly customized for each customer application due to technical parameters such as satellite orbit and coverage region geography. Examples of critical payload components include antennas, amplifiers, and receivers.

One other contextual aspect of the satellite industry must be mentioned here: a strong emphasis is placed on weight optimization due to the negative impact weight has on launch costs. As with any space sector, the communications satellite providers are intensely focused on the minimization of spacecraft mass, a critical factor in production and launch costs. This focus on weight creates strong incentives to tailor each component of a satellite to a specific set of mission requirements, creating a direct tension between satellite "performance" and commonality. Launching mass into orbit is expensive; is an easily quantified cost; and tends to drive satellite designs to be highly integral. As will be discussed later, high degrees of satellite subsystem integration complicate the bus-payload interface, allowing intended payload changes to impact the bus design. While the bus/payload concept appears to be a simple division of spacecraft functionality, the reality is much more complex.

The Company F case examined a bus-based series of communications satellites. The scope of the study was limited to fourteen satellites that either had already been launched or that were well along in the development process. These satellites were based on an evolving bus, or platform, that was and is intended to support multiple spacecraft designs. (See Figure 105.)

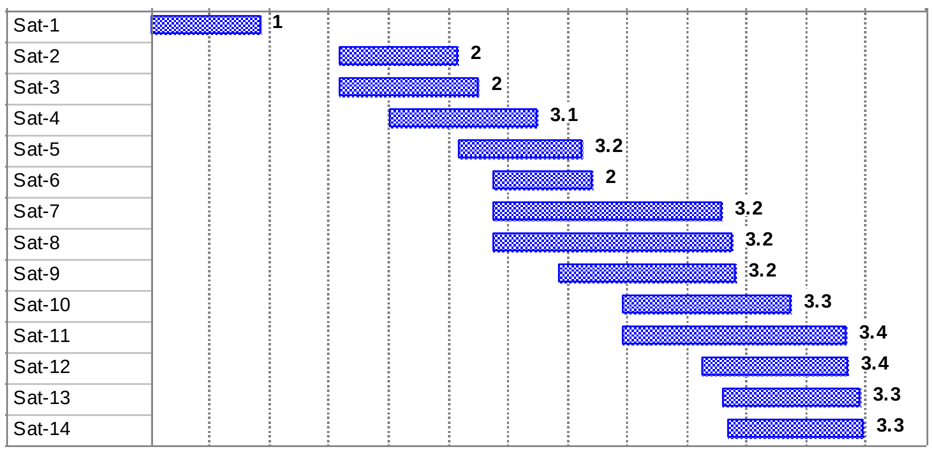

Figure 105: Satellites within the study's scope, including bus type designation. Bars indicate the period of time from initial order to launch date. The horizontal axis is time. Dates have been removed to preserve anonymity.

9.4.2. Brief History

The Company F bus and satellite program histories are highly interconnected: little in the way of bus development occurred outside of the individual satellite programs. Given this situation, the following description combines discussions of bus development with individual satellite programs. For the purposes of this discussion, the history is divided into the following periods: early bus efforts; scalable bus vision; early bus development; and bus expansion.

Early Bus Efforts

The roots of the scalable bus began with several early satellite programs (Sat-1, -2, -3). Reuse was a high priority within these programs due to resource limitations and the goal was to carry over as much of the previous satellite's bus as was feasible while still meeting new customer payload requirements. These satellite programs provided new customer functionality while also improving various aspects of what was a relatively immature bus at the time. Market uncertainty and resource limitations prevented the company from pursuing significant future development: development resources were focused on meeting the needs of the current program and leveraging previous development to the maximum extent possible.

Scalable Bus Vision

After testing the small satellite market, Company F realized that significant business opportunities existed for expanded coverage of the small satellite market; i.e., high power market opportunities existed within the small satellite segment. In order to cover the broader market, a scalable bus vision was created. This bus would support three configurations:

- Bus-3.1: low power
- Bus-3.2: medium power
- Bus-3.3: high power

According to the initial vision, the core bus would be the same across the three configurations with the exception of differences in key power system components, which were designed to be scalable. The differences between the bus versions would be relatively minor, with the result being that the bus would see increased total demand levels (the majority of the bus subsystems would be produced in quantities equaling the total satellite production volumes), while power capability and payload would be tailored to the requirements of each order. Through this approach, the addressable market would be expanded by approximately five times over the originally addressed market.

The bus vision was documented in the "Bus Design and Development Plan." Goals were established for total bus development cost and variable (production) costs. The development plan clearly described the need to address a range of applications; spelled out six mission scenarios for consideration; and stated that "these scenarios should not be used to point design the bus for each payload, but to assist the development teams in establishing bus performance ranges." The plan called for the use heritage components[60] (hardware and software) and to maximize common tooling and fasteners. Missing from the initial plan was a clear definition of the various bus configurations. The document was vague with reference to how many bus versions would be produced, in what order they would be developed, etc.

To summarize the bus vision, Company F clearly was thinking about commonality and bus strategies during the scalable bus planning phase, although the degree to which the vision was translated into an actionable plan with well-defined configurations is debatable. The lack of clarity in terms of bus definition and communication of this vision appears to have been a source of bus design churn later in the bus lifecycle.

Development of the Low Power Configuration

Satellite Program 4 represented the first customer sale of a low power version of the scalable bus. The initial vision of creating a scalable bus was incorporated into the Program 4 plan as little bus development had occurred prior to the order. This meant that a significant amount of bus development risk was coupled to the satellite program. The complexity of supplier relationships and of developing both a specific satellite and its underlying bus led to

[60] "Heritage" refers to the use of previously flight proven components. The high consequences of failure in the satellite industry (complete loss of satellite investment) have created a very strong interest in reuse.

development cost and schedule problems. As a result, the development strategy shifted from the creating a scalable platform that would support an entire product family to meeting the immediate needs of one specific customer. Most of the platform requirements were eliminated in order to produce a bus that met the Program 4 requirements. In particular, the ability for the core bus to extend to higher power was abandoned. The output of the program was a compromised bus (v3.1), that met the initially envisioned Low Power capabilities but did not support the higher power requirements.

While the scalable bus leveraged existing bus designs and experience as a starting point, the move to higher power levels created a high overall degree of change that rippled across the entire spacecraft bus. For example, a larger structure was required to support the higher power specification (larger payloads, increased solar power, increased thermal loads, etc.). Additional modifications were made to the Attitude Control System (ACS) and software.

After completion of Satellite 4, the Low Power capabilities were sold to a second customer. The sale provided a second opportunity to design the Low Power capabilities of the scalable bus and resulted in many improvements. True bus scalability was still unclear.

Expansion to Higher Power Levels

While the initial bus vision called for scalable power capabilities of up to the High Power level, the scalable bus vision had not been fully achieved through early development of the low power versions. The Medium and High Power configurations were still viewed as major market expansion opportunities. Reaching these higher powers required primarily thermal, power and structural changes and was initiated with research and development funding rather than being conducted within the scope of a specific satellite program. The bus modifications required to meet the higher power requirements resulted in "more changes than initially anticipated." Initial bus development was conducted prior to receipt of orders for higher power configurations. When orders were finally received, the new requirements drove additional bus development work due to new customer requirements.

A Medium Power (Sat-10) and High Power (Sat-11) configuration were sold to Customer X. The delivery of the two satellites was to be staggered, with the Medium Power configuration having a lead time of approximately 2 years and the High Power configuration having a lead time of approximately 3 years. Also, at the time of Sat-10 and Sat-11 development, two other satellite orders were also visible. The team knew that designing to meet the High Power requirements would meet the requirements of these other satellites. Follow-on bus development expenses were expected to be dramatically lower than the Sat-10 and Sat-11 development spends. Assuming the effort was successful, the output of these programs would be the "real" bus as described in the scalable bus development plan.

The initial vision was to design and build one scalable bus that would support the needs of both satellite programs and therefore, fulfill the initial scalable bus vision of supporting three power configurations with one basic bus. The program bid was based on plans for concurrent design and build of both satellites, with one program manager owning both satellites. Both orders were received as a pair, meaning that Company F knew up front about both satellites. Per the initial bus vision, configuration changes would be limited to the power system and supporting elements of this system. Elements such as the radiator and main bus structure would remain common across models.

Although the original plan was to develop one bus core that would support the Medium and High Power configurations, the final outcome was the creation of two similar but separate bus designs, due to an unanticipated difference in key thermal requirements of the two designs. The root cause of the unexpected thermal problem was the sequential manner in which the two satellites were developed, combined with the lead development effort being associated with the less capable (Medium Power) satellite program: development of the more demanding satellite followed development of the less demanding satellite by about one year. The result of this offset was that both designs were not at the same level of design definition at any given time. Knowledge about the Medium Power satellite was always at a more advanced state than knowledge of the High Power model. The team had to make decisions based on best estimates of the High Power model's requirements rather than detailed design information.

Beyond the Initial Low, Medium, and High Power Programs
Multiple satellites have followed initial development of the three bus configurations and the expectation is that these satellites should realize non-recurring engineering benefits associated with the bus reuse; in particular, reuse of the Medium Power and High Power configurations. Initial results appear to be mixed due in part to factors explained below.

9.4.3. Observations

1) **Company F's operations and culture are focused on the development, production, and delivery of individual satellites.** This focus is the result of a combination of program complexity, low satellite production numbers, and the historically custom nature of the satellite business. Satellites are developed in response to a specific set of customer requirements as opposed to the aggregate needs of a larger customer base.

2) **Program managers have nearly complete design authority over all program elements including the bus, providing the proper support for successful satellite program delivery while compromising the underlying bus.** Each program manager is incentivized around the specific performance, quality, cost, and delivery requirements of his or her satellite program. Within this incentive structure, the program manager is free to reuse existing subsystems, including those associated with previous programs, and may pursue reuse in search of the associated development cost, schedule, and risk reductions. This organic approach to reuse is much different than a policy that requires a baseline of reuse with deviations being granted by exception. Historically, bus changes made to support a program are believed to be, or are claimed to be, applicable to future programs. In other words, even though commonality did not hold up within the current program, commonality is believed to be applicable to the future.

3) **The bus is not actively managed as a core asset: a clear bus owner was not identified during the study; the overall bus strategy was not-well defined, communicated or represented within the organization; and formal platform development and management**

techniques did not appear to be utilized. The lack of rigorous bus management combined with strong program management has impacted bus stability and the realized benefits of the platform-based approach. In terms of bus strategy, an initial vision clearly existed for the scalable bus although this vision does not appear to have been well-documented in the form of market requirements specifications, requirements, etc. Without this structure, the bus definition is dependent on the team's collective wisdom and informal control, the latter being difficult in the current program-centric culture.

4) **The implementation of the bus vision has been challenged by the decision to conduct bus development efforts primarily within the scope of individual satellite programs. The impact of this approach has been bus development that was skewed towards the needs of each individual program rather than development of the underlying product platform and therefore, the needs of the greater market.** Implementation of the bus vision has been limited by Company F's program-centric culture. The bus has been repeatedly modified to meet the needs of individual programs rather than the superset of market needs and, as a result, Company F's bus investment history is greater and further spread out in time than would be expected given a formalized bus development effort. Multiple attempts were made to establish the bus, with the 3.1 being the first major attempt to translate the vision into a bus design. Problems with the program resulted in a scope reduction that produced a dedicated Low Power bus design, the 3.1. This bus met the needs of the immediate satellite program but was not scalable. Significant bus investments were incurred since the initial effort, as evidenced by the expenses for the 3.2, 3.3, and 3.4 configurations.

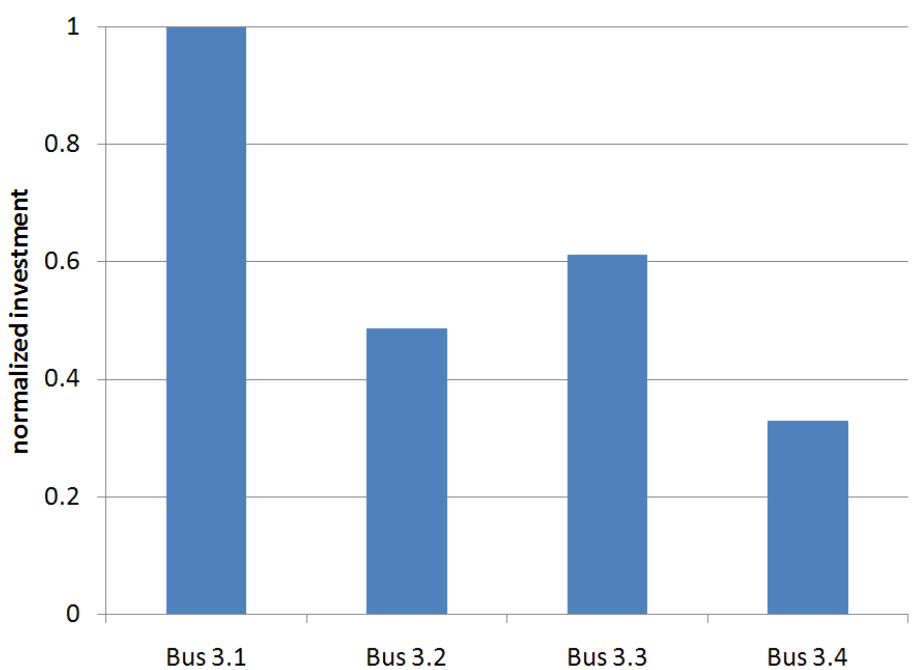

Figure 106: Normalized investment in each bus configuration. The Low Power bus is the combination of the 3.1 and 3.2 totals. The large 3.1 cost is likely due to other challenges faced by the program. Bus expenses have not decreased as would be expected if all configurations had been enabled by the initial bus design.

5) **The capabilities of the scalable bus have been incrementally expanded in order to meet increasingly demanding customer requirements.** While this expansion was partially envisioned during creation of the initial scalable bus vision, the full extent was not, and probably could not be, realized at the inception of scalable bus development (Sat-4). Major follow-on investments in the bus have been required to meet these expanding needs as evidenced by Company F's financial records.

6) **The sequential nature of Company F's low volume business makes bus requirements definition extremely challenging.** Company F manufacturers a few satellites per year, all of which have different requirements. These requirements change across customers and through time, as is the case with the trend towards increasing power. To properly develop bus requirements and the associated designs, all variant requirements must be understood and then combined to form a requirements envelop that addresses the superset of market requirements. As one interviewee said, this task "requires a crystal ball."

7) **The timing of satellite orders combined with the trend toward increasingly more capable satellites is a difficult operating environment: Company F is constantly faced with the decision of whether or not to add additional bus performance beyond the needs of a current program in order to reduce development effort on future, less certain programs.** In order to ease future development of more capable satellites, a current program must accept cost, lead time and/or risk penalties; an unattractive option to an individual satellite program manager. Additionally, the decision to enable future capabilities is based on a limited preliminary understanding of future requirements.

8) **Within a given bus configuration, development investments are generally decreasing, although many of these investments represent follow-on orders from existing customers. New customer orders of an existing bus version may drive significant bus NRE, an unexpected outcome given a platform-based approach to development. Tight coupling between the bus and payload designs results in increased payload development scopes being followed by increased bus development costs.** Tight coupling between the bus and payload results in large amounts of engineering work on the bus side of many programs. This phenomenon is most evident when a "new" customer purchases an existing bus version. Ideally, a bus version would be developed to meet an envelope of market requirements. Once this development was finished, changes would be extremely limited. While this is the case with follow-on orders from existing customers for the same bus, it is not always the case for new customers of a given bus configuration. The explanation appears to be the degree to which new payload development is undertaken in each case. In the case of follow-on satellite orders from an existing customer, payloads are similar, driving little in the way of new development. In the case of a "new" customer for a given bus version, larger payload development efforts are required and bus development expenditures rise with the payload workload. Trend drivers appear to be new requirements

that go beyond the capabilities of the existing bus and change propagation[61] across the bus-payload interface due to interface complexity.

The following figures illustrate the apparent correlation between bus and payload investments (Figure 107) and the relationship between bus configuration costs (development) and the number of units produced (Figure 108). The expectation is that reuse of a given bus configuration results in reduced bus development expenses due to configuration maturity. Figure 108 shows two anomalies: programs that utilized an existing bus yet invested more in the bus than the predecessor programs. In both cases, a reasonable explanation for high bus NRE spending on a later program is the mismatch between the requirements of a new customer and the capability of the existing bus. The observations indicate that the scalable bus design has not been robust enough to support new customer requirements. The net effect is new customer driven churn in each bus revision and higher than desirable follow-on bus NRE expenses.

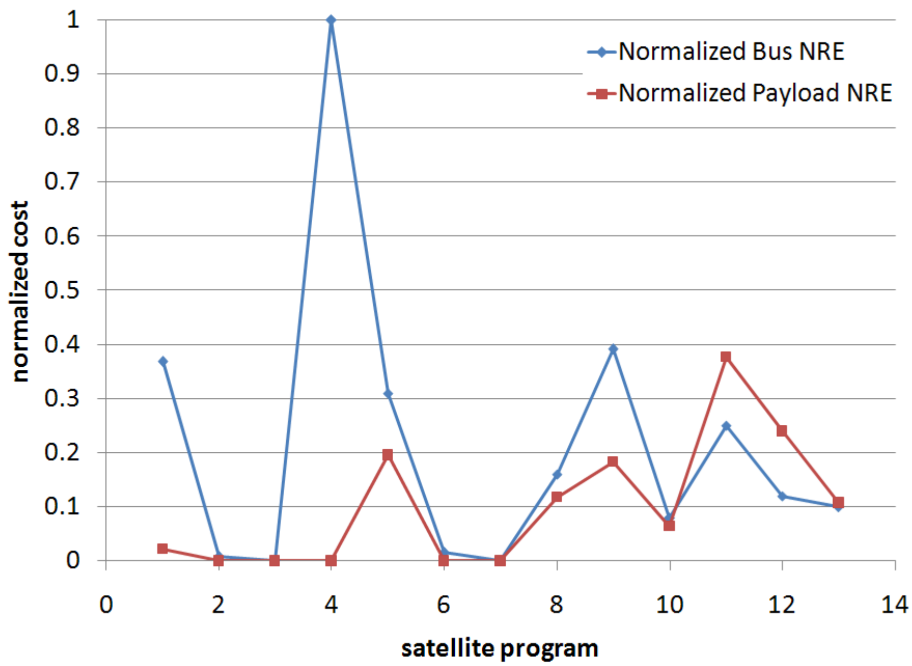

Figure 107: Normalized bus and payload costs illustrate an undesirable correlation between the two. Ideally, the bus would not be influenced by new customer requirements; i.e., the bus would be robust to new requirements.

[61] "Change propagation" refers to secondary design changes driven by a primary design change. For example, the addition of a channel to a satellite payload may cause unintended bus structure modifications. In this case, changes have propagated from the payload into the bus, an undesirable outcome.

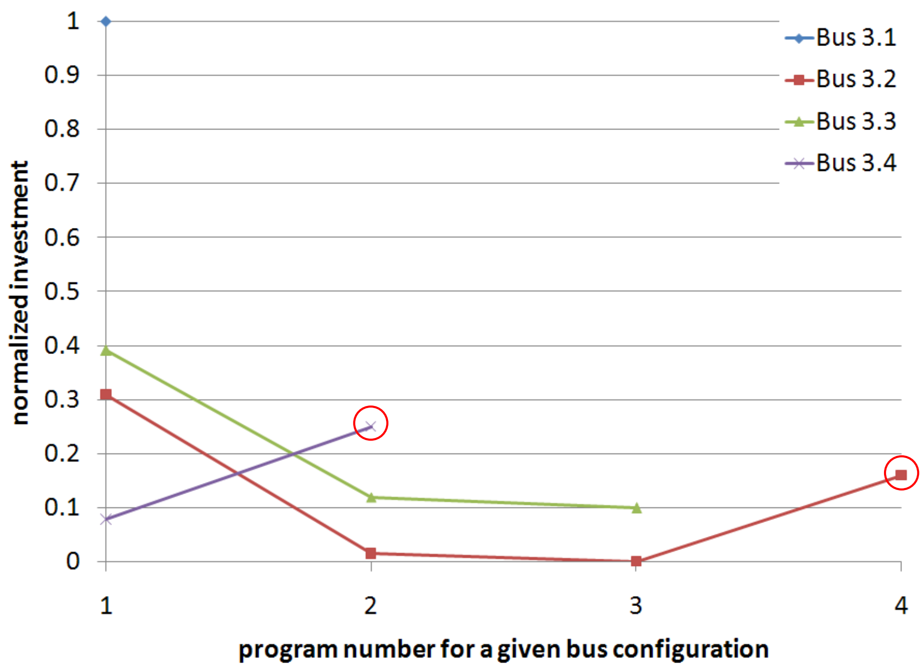

Figure 108: For the most part, reuse of a given bus configuration requires reduced levels of investment for follow-on satellite programs. Two anomalies exist and are both attributed to new customer purchases for a given bus configuration.

9) **Beyond new program requirements, the desire to incorporate knowledge gained from prior programs and the desire to incorporate new innovations both generate additional bus "churn."** The design cleanup category is required and expected throughout bus production.

10) **Customers place a strong emphasis on heritage parts as a form of risk reduction. Utilization of heritage parts is a strong reinforcement for the pursuit of commonality within the satellite bus and should drive commonality across programs.** Customers assign high risks to new or even modified subsystems that have not been flight proven. The emphasis on heritage parts serves to slow innovation within the industry but at the same time presents an opportunity for maintaining commonality. The customer is most likely to accept risks on aspects of the payload that offer increased value in some manner and least likely to accept risks on the bus portion of the satellite which primarily provides supporting functions. While innovation is impeded by the heritage culture within the industry, this emphasis does drive commonality in non-differentiating features.

11) **Functional groups such as the Integrated Product Teams (IPT's) and subsystem manufacturing centers have cross-program responsibilities and incentives to support common subsystems/components but limited design authority to pursue these opportunities.** IPT managers have visibility across multiple programs but assign employees to individual satellite programs. The IPT's provide analysis and recommendations to the program managers, but decisions about commonality ultimately reside with the program managers who are motivated to optimize their individual designs.

12) **The definition of "common" and the associated benefits of commonality both vary depending on the organizational function.** For example, Manufacturing defines commonality much more narrowly than Engineering. Manufacturing aims for exact repetition and realizes benefits from doing so. Commonality in manufacturing refers to exact part number matches and direct carryover of procedures and tools. According to one manufacturing representative, "small variations bite us in a big way." A proposal effort, on the other hand, necessarily involves a minimal amount of effort as the satellite order has not yet been received. The limited analysis simply cannot identify the true scope of changes that will be needed and tends to over simplify the impact of new requirements: everything looks similar from a high level view.

9.5. Case G: Semiconductor Manufacturing Equipment

9.5.1. Introduction

The semiconductor device industry is characterized by incremental performance improvements as broadly described by Moore's Law but more closely guided by the International Technology Roadmap for Semiconductors (ITRS). The ITRS roadmap specifies all key device performance characteristics for each technology generation (node) and serves as a way to coordinate the extremely complex web of technology development that must occur to create increasingly capable devices. Capital equipment companies, such as Company G, follow this roadmap for guidance on process technology advancements. The rapid pace of change drives incremental, as opposed to radical, advancement with high degrees of carryover from previous models that improve the cost, lead time, and risk attributes of new development programs.

Company G focuses on the implant segment of the semiconductor capital equipment business. The company has developed deep expertise in this area and is a leader in its segment. The company competes in the High Current, Medium Current, and High Energy market segments with the majority of its revenues coming from High Current and Medium Current. In terms of total sales, Company G deals with a small number (3 to 4) of highly influential customers. Another 10 to 15 customers exist.

The importance of customer retention places a lot of power and influence on the customer side of the relationship, which translates into strong customer inputs in product development and product configuration. Customers expect a high degree of product customization, which is both an outcome of customer needs to develop proprietary manufacturing processes and a historical artifact of the industry.

In addition to exerting strong influence on designs and product configurations, customers also typically have a need for product stability once a product configuration has been qualified for a particular device technology node. The semiconductor manufacturers strive to qualify the latest technology, then "lock-down" this technology for a period of time. The need to provide rapid incremental advancements combined with the need to support a given product configuration for potentially long periods of time creates a high degree of manufacturing complexity internal to Company G.

The Company G case study examined the development history and current status of the company's highest volume lines: High Current and Medium Current. The product lines are based on a platform strategy that utilizes common and similar elements to provide common functions to all products. Examples of platform elements include the control system; positioning system; wafer environment and handling system; and beam architecture. The platform is utilized for every production system that Company G ships today and is stated to provide high commonality in most components and procedures.

9.5.2. Brief History

The product history clearly indicates a strong coupling between the evolution of the platform and the various product lines. The purpose here is to present enough historical information to motivate the later discussion of case study observations rather than to provide an in-depth history of detailed changes. Figure 109 illustrates development start through to the last shipment date for all three product lines. The following discussion briefly covers highlights of the product line evolution and then discusses the evolution of the underlying platform.

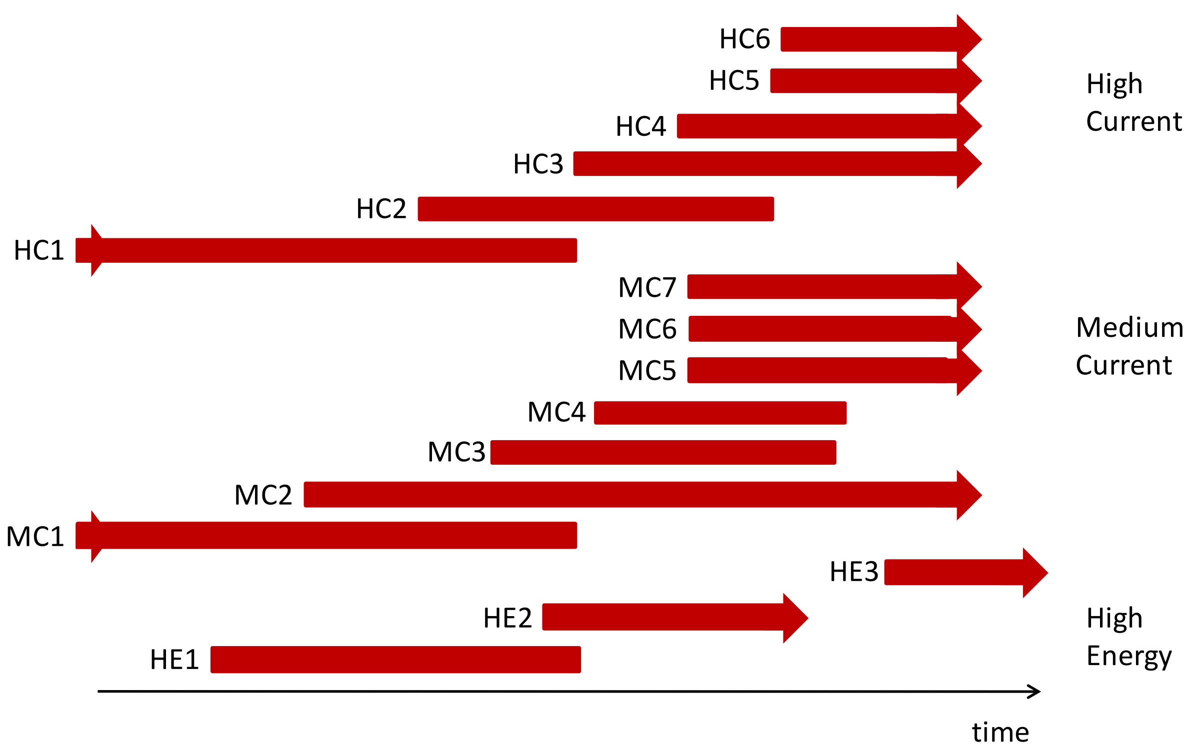

Figure 109: Company G's platform-derived product history. Bars illustrate the approximate duration of the development and production phases of the lifecycle. Splits between the two were removed due to proprietary information concerns.

Evolution of the Two Product Lines

Early development efforts were focused on the sequential development of single product models within each product line. Products were developed one-at-a-time and utilized the previous product model as a baseline. Improvements ranged across a broad spectrum: process performance, productivity, reliability, operations, and cost structure. The incremental advancements represent iterative maturation of Company G's implanter architecture and associated designs.

The last three Medium Current products within the scope of this study represent a shift from single-product to multi-product thinking. Up to and including the development of product MC4, development programs had produced single products that were incremental advancements of the prior model baseline. In the case of the last three products within the scope of this study, Company G needed to address a competitive situation that created downward price pressures. Marketing recognized the need for a family of highly related Medium Current configurations in order to allow varying levels of capability to be sold at varying price points. Products MC5, MC6, and MC7 were developed around this proactive strategy. The MC5 product represented a minor change from the prior MC4 baseline: the power distribution box was moved inside the main system enclosure. The MC6 product provided significantly increased throughput and tuning enhancements, while MC7 provided higher power levels. A significant degree of commonality has been achieved across the three products as is illustrated in Figure 110.

Through the proactive creation of a Medium Current family, Company G is better able to compete in the various Medium Current market segments. Lower capability requirements are met by product MC5; medium range capabilities (same power as MC5, higher throughput) are met with the MC6 product; and the needs of high-end customers (power and throughput) are met with the MC7. Customers are given a range of performance/price options and can choose based on their needs. In this manner, price is maintained on higher-end products, while still serving the needs of less demanding market segments.

The latest two products in the High Current product line were also designed in parallel, although in a more ad hoc manner than the Medium Current products. Figure 111 provides an analysis of the degree of commonality across the two latest High Current products and their immediate predecessor. Figure 112 shows the reduced levels of commonality when comparing across the Medium Current and High Current product lines: reduced levels of commonality are expected given the larger differences between product lines in comparison to the differences between the products within a given product line.

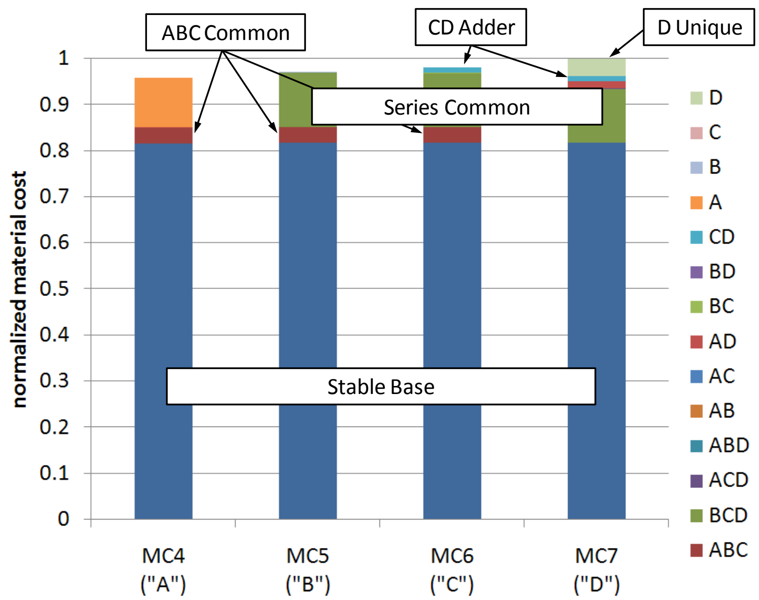

Figure 110: Company G data illustrating normalized material cost commonality across the Medium Current product line. Products "B," "C," and "D" were intentionally designed as a family and leveraged Product A as a baseline. All four products have over 80% material cost commonality. Products B, C, and D share an additional 12% of their material costs and Products C and D share an added 1%.

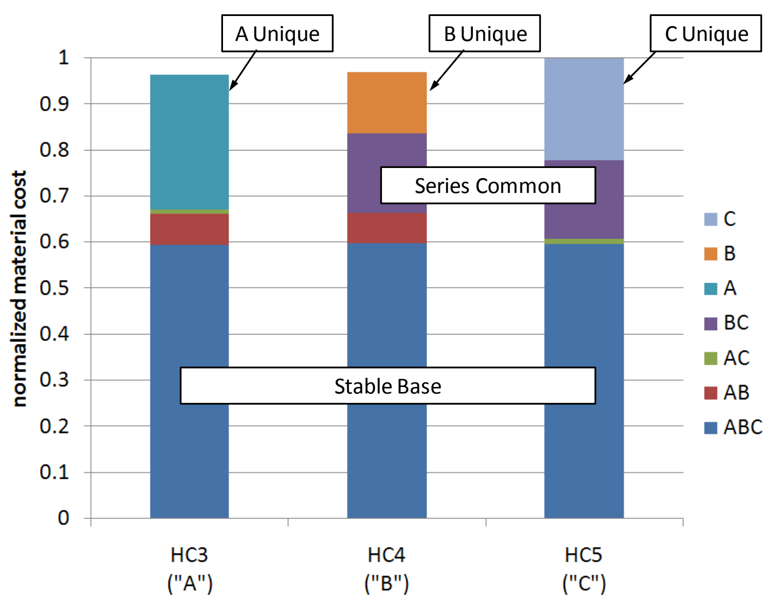

Figure 111: Company G data illustrating normalized material cost across the High Current product line. Products "B" and "C" represent a somewhat ad hoc family. 60% of the material costs are shared with the prior baseline product, "A." 17% of the materials by cost are shared between the newest products in the family, B and C. Also note that 7% of the materials from the prior baseline were carried forward to Product B but not utilized for Product C.

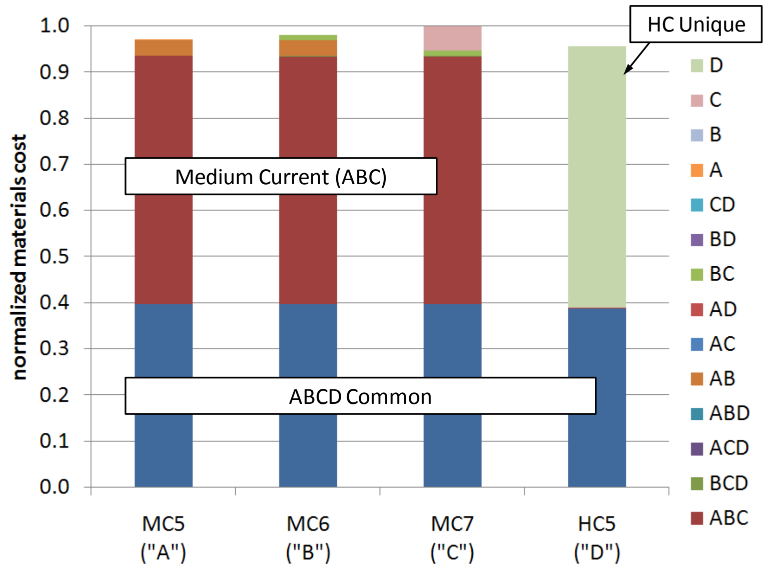

Figure 112: Medium Current comparison to HC in terms of normalized materials costs. As expected, a large component of the HC cost (59%) is unique with respect to the Medium Current products: commonality is higher within a product line than between product lines.

9.5.3. Platform Evolution

As was mentioned previously, the implanter platform consists of the software system, active beam compensation, "mainframe," and beamline architecture. The software utilizes a common core that is customized to the needs of individual customers. The beam compensation system links wafer positioning with beamline diagnostics to provide active process compensation. Beamline commonality at the part level is very low due to the unique performance characteristics of each system and the heavy influence of beamline components on these characteristics but the common architecture offers knowledge reuse benefits. The mainframe represents the factory interface, wafer handling, and wafer environmental control elements of the system.

The platform concept was formed through the combination of an acquired mainframe and an internal software project aimed at creating a robust software platform that could be leveraged across multiple products. The initial version of the mainframe was obtained through an acquisition. It was an integral part of a product that, based on the interviews, did not appear to have been intentionally designed as a common platform. Due to resource constraints, the initial mainframe was initially developed to support the needs of a single product, not the needs of a larger product family. The software project represented a serious (and highly successful) attempt to transition from "copy and change" software development in support of each new product model to a robust platform that enabled high degrees of reuse across product models. The vision was to create a common code baseline that would be configured to meet the needs of individual products and customer-specific options sets.

The initial mainframe was estimated to be approximately 70% common across all product models by one interviewee. This mainframe was significantly revised with the vision being to produce one mainframe that would suit the needs of all products. Key changes were aimed at throughput enhancement and cost reduction. A strategy of late differentiation in manufacturing was implemented in order to control the impact of options content.

The revised mainframe project was initially targeted to the Medium Current product line although the team realized that High Current products would also utilize the improved mainframe version. A few months into development, high level High Current requirements were added to the program in an effort to ensure the mainframe would be capable of meeting the needs of both product lines. High Current requirements additions were limited to the most pressing needs with smaller features and requirements planned for later additions. The actual development effort focused on meeting the nearer-term Medium Current needs at the expense of foregone opportunities in support of future High Current programs. Team members realized that simultaneous design for both Medium and High Current applications would have been much more effective but the Medium Current program schedule and resource loading constraints prohibited this. Additionally, at the time of development, High Current production volumes were very low, meaning that the High Current team had a limited ability to influence platform requirements.

Opinions of the current levels of mainframe commonality and the impacts of these levels ranged broadly within the organization. Engineering tended to focus on similarity of designs and architecture (e.g., the beamline architecture), which is believed to be very high. Engineering also tended to understate the impacts of diversity on the manufacturing line. Manufacturing provided the most pessimistic estimates of commonality (e.g., 15% common parts, limited process commonality) as the manufacturing organization focuses on exact part number matches and process carryover.

A tour of the actual mainframe final assembly line demonstrated significant differences between the different hardware configurations, while also highlighting the strong software system success. Major assembly differences started with the first assembly station. Including an in-development product, there were 3 base frames, 4 process chambers, and 2 wafer handler chambers that could be combined at this station. In other words, there was no core hardware foundation upon which various mainframe configurations could later be built. Feeder lines for mainframe assembly have similar complexity levels in areas such as pumps (three 250mm, two 320mm, and two 400mm). The pump options drive major differences in cables, harnesses, and routing. Upon arrival at the end of the mainframe assembly line, the discussion switched from hardware to software. A control system test engineer stated that the software systems are highly common from the standpoint of configuration and test: the common software has achieved its mission of supporting many hardware options through easily managed configurations.

Several factors have contributed to increases in the number of mainframe configurations and options over time. First, Company G has continuously created performance enhancements that generate additional revenues at attractive margins. Examples include the high throughput option and improved wafer holder that improves process control. Recognition of increased revenues from these options requires the retention of a lower cost and performance alternative, thereby increasing the number of supported options. Second, individual customer preferences drive creation of new options and make their future elimination difficult. Many of these options are driven by customer desires to maintain common elements across their entire equipment set that extends beyond Company G's product offering. Examples in this category include selection of pump and mass flow control suppliers. Third, customers attempt to maintain stability across lifetime buys of a given product once they have qualified that product for a specific process step. After process qualification, equipment changes become highly undesirable, unless directly tied to safety or known performance issues. Some customers have forced equipment companies such as Company G to lock down specific product configurations and to maintain these configurations for the duration of sales to that specific customer. While some changes are allowed, the vetting process is laborious and costly.

9.5.4. Platform Benefits

Product development investment data was obtained for the newest implanter programs in both product lines and was utilized as a check on platform benefits. In-line with the expected benefits of platforming and reuse, the data trends illustrated a reducing investment with time in the case of each product line. The average investment over the latest three Medium Current products was less than one fifth of the original product investment. (The cost data analysis was removed from this summary report due to proprietary information concerns.)

9.5.5. Observations

1) **The platform has significantly reduced the cost of product development due to high levels of component reuse and knowledge carryover.** Development of the most recent Medium Current products cost less than one fifth of the initial Medium Current product development cost. Likewise, recent High Current product costs are roughly half the cost of an early High Current product.

2) **Company G's historical approach to commonality is best characterized as "reactive reuse" of modules and parts that were developed for prior programs with little consideration of the needs of other programs (present or future).** The fast paced, incremental nature of the semiconductor capital equipment industry has created a strong emphasis on reuse from prior product models as a way for Company G to limit its development costs, times, and risks. During new product development, the prior product model is used as a baseline that is modified as needed to provide the customer with new levels of performance. Most reuse occurs between different generations within a given product line (e.g., High Current), with more limited carryover occurring across product lines (e.g., from Medium Current to High Current).

   Reuse has been characterized as "reactive" because little forward-looking development is conducted. New or improved system elements are designed within the scope of an individual product development effort in order to meet the needs of that specific program. While future needs may be considered informally, a program manager who is responsible for the current product makes the ultimate decision in the best interest of his or her product.

Through the implementation of Platform Technology Teams (two years ago), Company G is starting to transition from "reactive" to "proactive" reuse of modules and parts. As the organizational change continues to take root, improved pursuit of common module/part development can be expected.

3) **Commonality is highest between models within a product line (e.g., Medium Current), although commonality also exists across product lines, with the strongest ties being between Medium Current and High Current.** As one example, an internal analysis of generational commonality between two recent High Current products identified 71% of the total material dollars as being common. The same analysis performed between two products within the Medium and High Current product lines produced a much lower commonality level at 44% of the total material dollars. Creating commonality across products is much more challenging than maintaining commonality between a new model and a prior baseline. The latter is much more natural, especially given the fast-paced, incremental nature of product development within the semiconductor capital equipment industry.

4) **Company G follows a strategy of product model retention rather than model replacement, a strategy driven by attempts to retain margin through multiple equivalent offers and customer lock-in on specific configurations. Model retention has increased manufacturing complexity and cost.** Company G still builds most of the platform-derived products that it has developed over the last decade. Each new product introduction represents the addition of another model to the existing manufacturing mix. The result is an increase in manufacturing complexity and a reduction in economies of scale.

   Two reasons for model retention were identified during the course of this study. First, Company G utilizes its suite of products to provide customers with multiple equivalent offers. Through this approach, Company G is able to maintain higher prices (and margins) on its newest products, while still offering customers the option to purchase a lower price (and margin) product. Second, some customers expect a previously purchased configuration to be available long after Company G has released a new product model. Customers make changes at each new technology node but desire stability in between nodes in order to avoid process requalification costs.

5) **While the model retention strategy likely increases the product cost structure overall, this cost structure increase is offset by the manufacturing benefits of reuse from prior models.** With model retention, direct carryover (reuse of the exact component or subassembly) maintains economies of scale in manufacturing. Without model retention, the benefits of reuse apply primarily to non-recurring development cost, lead time, and risk reductions.

6) **Semiconductor chip manufacturers desire high levels of OEM component commonality across their entire fabrication facility (or portfolio of facilities), creating a direct tension between this desire for commonality and Company G's desire to limit product configurations. Company G's product configuration complexity must increase in order to enable customer complexity reduction.** As a systems integrator, Company G utilizes many OEM components that require service and replacement during field operation. Examples include vacuum pumps and mass flow controllers, each of which is produced by several

suppliers. Many semiconductor manufacturers try to standardize on a selected set of brands, although each manufacturer selects its own unique set. For example, fabrication facilities often enter into agreements with vacuum pump suppliers. These agreements are fab wide and they become constraints on the capital equipment suppliers, the effect of which is to increase options content. The fabrication facilities realize a benefit of commonality, while the capital equipment supplier incurs a penalty due to the diversity required to satisfy all customer needs.

7) **The small number of customers (10-20), limited opportunities for sales (beginning of each technology node as defined by the International Technology Roadmap for Semiconductors), and the historically custom nature of the industry have contributed to significant product customization. Saying "no" to a customer is difficult.**

8) **Ownership of product family commonality is informal at Company G. A clear strategy for commonality was not identified.** Clear ownership exists for some of the subsystems owned by the functional teams (e.g., gas delivery), but a high level strategy and owner were not identified. Senior management ultimately owns commonality decisions, but obviously must focus on many other priorities.

9) **The platform does not appear to be rigorously managed as an internal product. The platform is subordinate to the individual products and, as with other system modules, tends to be utilized as a baseline from which design modifications are made to meet the requirements of a new program.**

10) **The platform hardware set is tightly coupled to differentiating product features, creating a tension that has led to divergence across mainframe configurations. Mainframe diversification has resulted in increased manufacturing complexity and the loss of economies of scale created by splintered product volumes.** The implant process is significantly influenced by certain aspects of the platform, creating strong drivers for design divergence due to real customer differentiation needs. As a result, the platform variants have significant differences at the part level; for example the first platform assembly station manages multiple types of chambers and frames. The impact of divergence has been a reduction in the true scope of the platform. In addition to increased assembly complexity, individual parts are procured at lower rates and higher costs.

11) **The control system (software) represents a significant success in terms of commonality and the realization of the benefits of commonality. The control system has replaced the "copy and change" software development model with a platform approach. High levels of code reuse have resulted in significant software development and support cost reductions.** The software relies on a common core, combined with product specific code that manages the unique operational needs of each product. Numbers of lines of code were provided for a typical product, with greater than 95% of these lines of code being common across all products. Code revisions for new models require between 10% and 25% of the labor investment of the initial baseline. Support costs are also kept in check through the same high levels of commonality.

12) **Backward propagation of changes, or the insertion of new improvements or fixes into existing product designs, has minimal benefits, yet high costs. The combination of Company G's model retention strategy and the lack of incentives for backward propagation of changes has created long term manufacturing complexity.** "If it isn't broken, don't fix it" is a commonly expressed view within Company G: the business case for incremental improvements to existing systems is typically unattractive due to high switching costs and limited benefits. High switching costs are the result of design modification costs, testing costs, and change management costs associated with customer desires (or very strong requirements) for product configuration stability.

13) **The team is keenly aware of the "commonality tax," or the additional variable cost associated with increased, but unneeded capabilities (e.g., increased power supply output) for a given market segment. This "tax" is one of the more tangible penalties of commonality and tends to be weighed heavily in decision making.** Company G avoids paying for unneeded capability, an easily quantified cost. Additionally, Company G desires to charge for increased capability whenever it is included in the system, a further incentive to match component capability to system requirements. Commonality benefits such as non-recurring engineering cost reduction, economies of scale in procurement, and lifecycle benefits such as inventory reduction and common training may not be as clear as the commonality tax.

14) **The business case for commonality does not appear to be well-developed. The current limited focus revolves around the evaluation of potential development savings (cost, lead, and risk) and manufacturing savings. Missing are a formalized approach to evaluation and the consideration of lifecycle benefits and penalties from the perspectives of both Company G and its customers.** A common perception is that the business case for commonality is marginal rather than compelling, although the business case for commonality does not appear to be well-developed from the perspective of lifecycle costs and benefits. Commonality opportunities are currently evaluated in an ad hoc manner. "Big picture" studies that evaluate suites of commonality opportunities and benefits such as lead time reduction, supplier cost leverage, manufacturing complexity reduction, field inventory reduction, etc. have not been conducted. Additionally, support groups such as Manufacturing accept Engineering and Marketing changes as requirements. Support groups do not regularly quantify the costs of these decisions from the perspectives of their departments, nor do they utilize this information to challenge proposed changes.

15) **Program managers have traditionally had the most influence on product development decisions, driving individual product optimization at the expense of commonality. The organization is transitioning towards a functional structure and culture that will balance the required individual product focus of program managers with the broader responsibilities of functional managers who have incentives to develop common or similar systems across products.** The new organization is structured to improve commonality and reuse across product lines although program managers still necessarily retain a high degree of influence over product design decisions.

16) **As part of the organizational and cultural shift, development is moving from product-specific module development to common module development with the goal being to better leverage development resources.** At the current time, functional teams are funded primarily by individual product development programs as opposed to receiving direct funding for common technology development. The current funding scheme limits the functional teams' abilities to develop truly common modules. At the time of the interviews, the functional organization appeared to be limited to suggesting new ideas for common development to individual program managers, who make support decisions based on the needs of their individual programs rather than the needs of the larger product portfolio. Some of these suggestions produce immediate cost reductions and/or performance increases from the perspective of the current product development effort and are readily accepted. These opportunities are aligned with the needs of the larger product portfolio. Other opportunities may have benefits from the standpoint of Company G's entire product portfolio but have penalties or minimal value from the standpoint of the potential program that would fund development. These opportunities are currently lost as program managers are incentivized to optimize their program metrics rather than the larger goals of the corporation. The two are not always aligned.

17) **The newest three Medium Current products represent the successful proactive development of a family of products based on an initial strategy for commonality.** A vision for the three products was created by Marketing and was based on the previous product model. The primary motivation for the strategy was a competitive entry that would drive price competition in a lower performance market segment. The three product approach enables Company G to compete in the lower priced market while protecting price in higher performance segments.

    The High Current team has followed a similar, although less proactive, approach with the development of its two newest products. While an initial derivative strategy did not exist, development schedule delays associated with the new products created an opportunity for the High Current team to switch to a derivative strategy based on awareness of the Medium Current team's prior success.

9.6. Case Study Introduction (sent to potential case study companies)

Managing Commonality during Product Family Development

Ryan Boas, PhD Candidate in Engineering Systems, MIT

Commonality (i.e., sharing parts, processes, interfaces and infrastructure across product family members) offers potential benefits such as reduced product family lifecycle costs, decreased follow-on product lead times, and decreased follow-on development risks. Realizing the full benefits of commonality as planned for in the initial business case can be quite difficult. Commonality strategies often evolve during development due to changes in requirements; learning in design and development; the availability of new technologies; and for reasons associated with corporate culture. Understanding this trend and its management implications offers a path to increased enterprise profitability.

Case studies spanning across several industries (e.g., aerospace, automotive and high tech) are being utilized to explore 1) the changes commonality strategies undergo with time and 2) the different approaches to commonality given sequential versus parallel development of product families. The case studies reside within a doctoral research program aimed at improving the overall management of commonality.

The proposed case study within your organization will focus on understanding the selected program's approach to managing commonality in parts, processes (e.g., manufacturing and logistics) and infrastructure. Emphasis will be placed on understanding the initial plan for commonality; management actions taken to develop, measure and control commonality across organizational functions; and an examination of the evolution of this plan over time. Interviews with senior managers (program management, engineering, manufacturing, field operations, systems and business development) and other key employees will be utilized to understand the program's approach to managing commonality and to reproduce the development history from the perspective of commonality. Where applicable, data will be utilized to link quantitative snapshots of the program to this history.

There are several benefits to participation in this study. Your organization will obtain an external analysis of commonality across the history of the selected program. The findings from this analysis will aid future product family decisions on both the selected program and future programs within your organization. In addition to direct findings from this particular case study, you will gain access to non-proprietary findings from the other cross-industry studies, ensuring access to best practices and the pitfalls that other organizations have faced.

To support this case study, a contact person in your organization is needed to provide assistance with logistics such as interviewee selection and interview setup. A site visit of approximately one week will be utilized to conduct interviews and, given mutual interest, to begin follow-on data collection. The proposed start of this study is April, 2007, with a final report being delivered by June, 2007.

9.7. Discussion Guide for the Case Studies (sent to interviewees)

Managing Commonality during Product Family Development

Ryan Boas, PhD Candidate in Engineering Systems, MIT

Discussion Guide

This interview is part of a series of cross-industry case studies investigating the management of commonality in product family development. The studies are investigating the changes commonality strategies undergo throughout the program lifecycle, but in particular, during the development phases of a product family.

The goal of our discussion will be to discuss your experiences with the program. The questions below are indicative of questions that will be utilized to guide our discussion. The discussion is intended to be semi-structured: key topics will be covered, as opposed to explicitly discussing answers to each question.

Product Family Evolution:

- Describe the product family history. What variants were planned? Developed? Produced?
- What was the product family strategy at the inception of the program? (How many variants? Design/build all variants at once vs. sequentially?)
- What was the initial strategy for commonality? How was this strategy arrived at?
- How did the plan for commonality change with time?
- What were the key program events/decisions that drove these changes?
- In the early planning phases, was there any discussion around changing levels of commonality? Was a sensitivity study done on the economic impact of changing levels of commonality?
- Were any attempts made to avoid the changes? If so, please describe them.

Costs and Benefits of Commonality:

- What do you perceive to be the benefits of commonality?
- What do you perceive to be the costs of commonality?
- How were the costs and benefits of commonality analyzed for this program?
- Where is commonality important? Why?

Other

- How was the program organized?
- Who was responsible for commonality within the program? How were deviations approved?
- Are any efforts being made to increase or regain lost commonality?
- If a sequential development effort, how were the interests of future variants represented? Was this effective?
- How is "common" defined within your program? How has this definition changed over time? Do you track varying levels of commonality? (e.g., cousin parts)
- How was commonality measured? Reported?

R. Boas 3/11/2007