

Identification of Leading Indicators for Producibility Risk in Early-Stage Aerospace Product Development

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Submitted to the MIT Sloan School of Management and Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degrees of

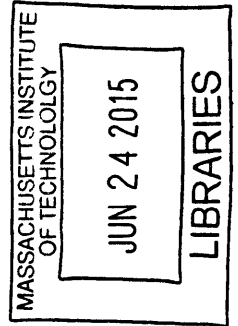
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and
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Abstract

Producibility is an emergent property of product development and manufacturing systems that encapsulates quality, product compliance, cost, and schedule. Detailed product definition and process variation have traditionally been a focus area for understanding risk for producibility losses. It is proposed for this investigation that while assumptions inherent to product configuration and process selection can significantly impact producibility, producibility risk and realized producibility losses are primarily indicated by organizational design assumptions and associated phased implementation of programmatic governance.

This premise is systematically explored through an assessment of organizational dynamics and product development performance within Aerospace Corporation X. An extension of the hazard analysis technique System Theoretic Process Analysis (STPA) is invoked for leading indicator derivation from assumptions underlying causality of inadequate producibility control. Indicator integration with risk management processes is outlined, and a combination of expert-assessments and quality loss correlation are used to validate indicator significance.

As a result of these investigations, it is concluded that functional isolation, phased capability and control, and differing performance incentives are central to producibility loss. In addition, these factors are deemed to be more important than product feature-based sources of producibility risk. Extension of STPA for indicator identification is validated and recommendations are provided for implementation of a leading indicator monitoring program.

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Content resulting from the associated practicum and supporting organization that form the basis for this work are subject to intellectual property protection. Therefore, all included company private and proprietary information has been removed or masked to prevent information disclosure. This includes, but is not limited to, unique business processes, manufacturing process capability, program metrics, product requirements, product performance, product attributes, and quantitative data. In addition, the name of the subject organization and departments have been modified to prevent traceability. If disclosure of censored information is desired by members of the practicum organization, please contact the author through the Leaders for Global Operations program.

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Chapter 1

Introduction

1.1 Scope of Investigation

Risk is defined as a combination of the likelihood of occurrence and consequence of an unfavorable event that can lead to a loss. Producibility is an emergent property of product development and manufacturing systems that encapsulates the ability to produce a product within cost and schedule constraints, while maintaining a target level of quality and producing a product compliant with applicable requirements. Given that producibility is an outcome of a breadth of design and operating activities, associated risk is not traditionally identified in product development until significant detail in product configuration and the production system is understood. The difficulty with this phasing is that a disproportionate amount of product and process definition, and therefore cost and complexity, is anchored at the earliest stages of product development before producibility risk can be estimated. A systematic approach to identifying indicators of producibility risk is needed that can address the complexity associated with modern socio-technical organizations and innovative aerospace products.

The methods and findings presented in this investigation focus on large-scale, new product development with the goal of identifying leading indicators of producibility risk early in the product development process. Focus is placed on segments of aerospace products that require externally-sourced fabrication, processing, and sub-assembly based on provided configuration, with subsequent major and final assembly internal to the parent organization.

This sourcing framework was selected for this investigation to capture the recent aerospace industry trend of shifting a large percentage of cost-of-goods sold and development risk into the respective supply base for a given product. Application of the presented methods to products with any combination of internal or external sourcing for constituent segments is possible in order to develop findings applicable to a specific organization and product development system. Similarly, the presented investigation focuses on a socio-technical system creating physical components and assemblies, but the principles can be transposed to complex products in any domain and industry. Value of the developed methods is not dependent on the specific application, but rather the ability to leverage a systematic approach to identify producibility risk at a point in the product development continuum when it can be assessed and mitigated.

1.2 Supporting Practicum and Company Overview

The problem and hypothesis presented in this investigation, along with the proposed approach and methods developed to assess producibility risk, are the result of an approximately seven-month, first-person, engagement with a large aerospace manufacturer, referenced as Aerospace Corporation X. While anonymity must be respected, specific attributes of organizational structure and new product development programs at Aerospace Corporation X are used to develop frameworks applicable throughout both the aerospace industry and any other industries developing products with significant complexity. A discussion of organizational dynamics will also be presented to the greatest extent possible to aid application of these concepts to other organizations. This section presents a limited overview of the operating characteristics and market performance for Aerospace Corporation X to support subsequent analysis of organizational performance. In addition, an introduction is provided to a specific product development effort within Aerospace Corporation X that will provide the foundation for a supporting case study within this investigation.

Aerospace Corporation X has an established history of pioneering and innovation in both commercial and military aerospace air vehicles designed for a variety of applications. The business is headquartered in the United States and currently produces military and

commercial air vehicles, aftermarket parts for aircraft and helicopters, and aerospace service solutions. Aerospace Corporation X resides under the umbrella of a larger U.S parent holding company with subsidiary businesses producing a variety of technology-dependent products for the military and commercial sectors. Aerospace Corporation X currently has six core military products and two core commercial products in full-rate production, with continuous production on some of the core product lines since the 1970s. Military products serve both the United States government and foreign governments. In addition to full-rate production, Aerospace Corporation X is currently in various phases of design, test, and initial production for four derivative and three new product types. Additional non-core product lines are produced through acquired aerospace subsidiaries. Internal production operations are spread across four facilities within the United States and three international locations. The company also has an expanding network of engineering design centers in both domestic and international locations. Aftermarket services extend the reach of the company to five continents with total employment exceeding 15,000 people. In addition to company operations, Aerospace Corporation X has a large domestic supply base with international suppliers primarily located in Poland, China, and India.

While serving both commercial and military markets, the primary business for Aerospace Corporation X has been centered on domestic military contracts. The balance between the percentage of sales revenue from U.S military products and all other sales is depicted in Figure 1-1 for the period of 2008 to 2013.

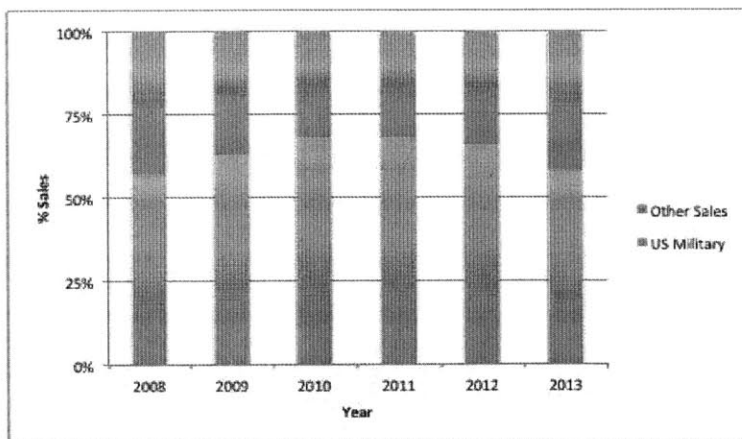


Figure 1-1: Proportion of US military sales to all other sales for Aerospace Corporation X over the period from 2008 to 2013

The dependence on both military and domestic sales means Aerospace Corporation X is highly dependent on U.S. fiscal policy. Efforts have been made to diversify the business into commercial and international markets, but as shown in Figure 1-2, the trend in percentage change in year-over-year sales follows U.S. defense spending rather than the U.S. G.D.P., even with some separation of international sales performance in recent years.

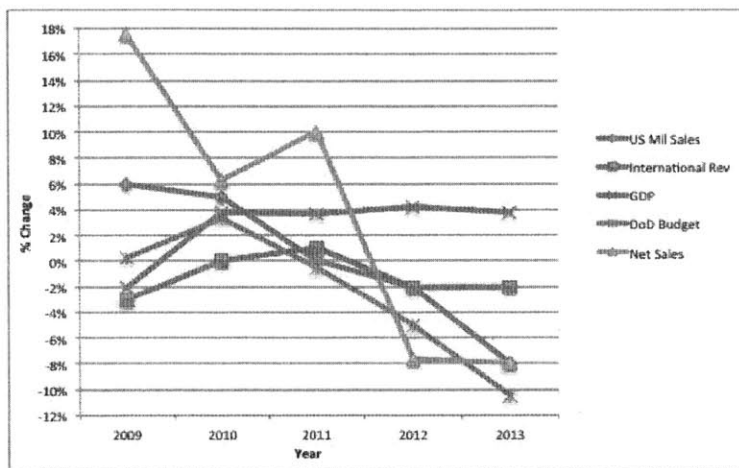


Figure 1-2: A comparison of Aerospace Corporation X percentage change in annual sales with annual change in U.S. GDP and U.S. DoD spending.

One potential short-run, mitigating factor for this domestic military market dependence is the durable nature of the products and production backlogs associated with development and build cycles. Aerospace Corporation X has seen recent growth in its production backlog over the period of 2009 to 2013, as shown by the percentage change in backlog data presented in Figure 1-3. This expanding backlog increases stability in production demand in the presence of sales volatility, notwithstanding military contract cancellation risk. Unfortunately, more significant volatility is observed in operating profit than sales, signifying that operations are unable to take advantage of the backlog to bolster business performance. While partially attributable to the nature of military deliveries, this volatility also signals that there may be opportunity for improved responsiveness within the supporting development and production systems.

Even with predictable demand and realized opportunities in operations, U.S. government acquisition oversight and margin constraints challenge the ability to improve cash flow for a large percentage of Aerospace Corporation X products. As with most U.S. Department of

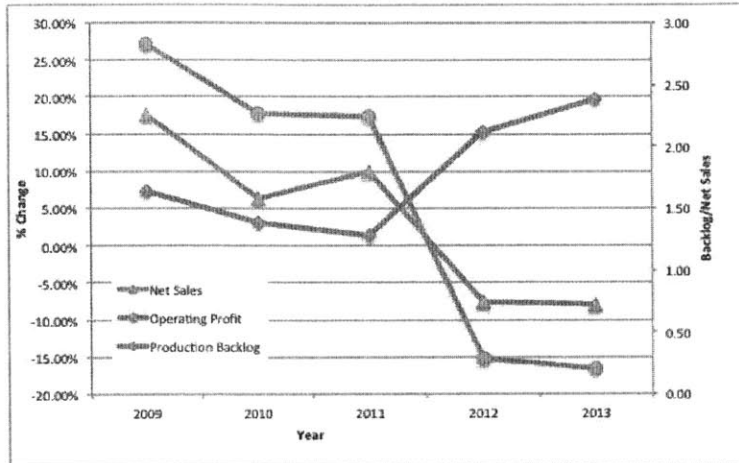


Figure 1-3: Relationship between percentage change in net sales, profit, and the production backlog for Aerospace Corporation X for the period of 2009 to 2013.

Defense (DoD) contractors, margin is subject to the transition in new contracts from a cost-plus model to firm fixed price or fixed price plus incentive fee contracts for new products. While an in-depth exploration of defense contracting is beyond the scope this investigation, this transition has constrained the amount of available incremental development funding and increased the importance of operating efficiency on U.S. government product programs at Aerospace Corporation X. The presented dependencies and externalities will be considered in this investigation as part of the socio-technical governance impacting producibility.

Finally, it was previously noted that a specific product development effort at Aerospace Corporation X will be leveraged in this investigation to understand governance for producibility. The case study product program is for development of a military product that is a derivative of an existing product in nomenclature, but is entirely new from a configuration and technology implementation standpoint. The program has been challenged by factors spanning the product development lifecycle, from requirements and technology maturation, to execution delays, fabrication and build non-conformances, performance shortfalls, cost growth, and contract conversion. Currently the project is over three years behind the original plan with most of the growth in the program occurring after configuration for the product was defined. The first test flight, a major milestone, is continuing to slide at the time of this investigation with similar slides in operational testing and low-rate production. Masked program performance data and temporal organizational structure are presented to develop

critical understanding of aerospace product development methods. Study of this particular product development effort will be transposed into an analysis of producibility governance and retrospective assessment to validate developed risk assessment methods.

1.3 Project Motivation and Related Initiatives

Product quality and product compliance with requirements are outcomes of effective producibility risk management. The aerospace industry, in both commercial and military markets, is facing increasing challenges traditionally faced by non-durable industries, namely global capital market uncertainty, growth in outsourced production, and reduced time-to-market expectations. Coupled with the complexity of aerospace products, rate of technology change, and regulatory oversight, methods are needed to maintain or improve quality and product performance in conjunction with controlling cost and meeting customer commitments. While subject to the noted challenges to varying degrees, Aerospace Corporation X has also been challenged by new product quality and performance impairments, which have driven higher non-recurring costs and delayed product delivery to customers. Improved methods to identify risk early in the product development cycle are desired by Aerospace Corporation X to allow for effective resource allocation and prevent early anchoring of risk in product and process definition. Given the noted challenges for Aerospace Corporation X, producibility is the product development program attribute under scrutiny for improved internal risk management. Methods proposed in this investigation for systematic identification of leading indicators for producibility risk, along with associated risk management practices, address this improvement goal and provide opportunities for improved industry practice.

The practicum investigation and resulting method development occurred as a complementary effort to a cross-functional manufacturing readiness initiative within Aerospace Corporation X. The manufacturing readiness initiative was directed by executive Engineering and Operations management to identify improved methods for operational efficiency and risk management throughout the product development process. The effort was initiated with a process study and mapping exercise for the entire product development cycle. Areas of existing challenge from recent development experience along with proposed ideas for im-

provement were elicited from Engineering, Production Operations, and Business Operations team members. Recommendations were then aligned to the following sub-team focal areas for further study and implementation planning:

- Manufacturing Planning
- Design to Cost
- Production Part Approval Process
- -Illities and Risk Management
- Producibility Assessment Tools and Design Guidelines
- Tooling Processes
- Supplier Management

Identifying leading indication for producibility risk fell within the Illities and Risk Management team purview. Through recurring sub-team sessions and targeted engagements with functional teams within Engineering and Operations, both product development program performance for the included program case study and models of organizational governance for producibility were constituted. The resulting methods developed and ultimate risk management approach were provided to the parent organization to facilitate internal product development risk management and supply chain risk management. Continued refinement and empirical validation will be completed through ongoing product development efforts at Aerospace Corporation X.

1.4 Problem Statement and Hypothesis

Addressing aerospace production shortfalls that result from the incompatibility of product definition with manufacturing capability requires an assessment of systemic control for producibility. Characteristics of detailed product definition and manufacturing process variation have traditionally been a focus area for understanding of producibility shortfalls, given the relationship to quality control, but organizational and programmatic factors must be considered for their influence on workforce integration and organizational dynamics. The impacts of inadequate producibility control can impact both new product development as well as incorporation of change within mature products.

Assessment of common aerospace stage-gate product development processes in their en-

tirety provides a breadth of organizational and product characteristics that could be hypothesized as indicators of producibility risk beyond product technical product definition. It is proposed for this investigation that while assumptions inherent in product requirements and configuration can significantly impact producibility, producibility risk and resultant producibility losses for a given product program are primarily indicated by organizational design assumptions and associated phased implementation of programmatic control. Specific control assumptions that are the focus of this investigation for their indication of producibility risk are associated with the following aspects of programmatic control:

- Degree of development process isolation between functional and external groups
- Phased maturation of organizational capability
- Phased maturation of process control
- Explicit and implicit performance incentives

The significance of dynamic behavior in organizational product development and market strategy must not be overlooked for both its impact on risk identification and mitigation. Exploration and validation of the proposed drivers of producibility risk must include assessment of temporal governance with an organization. Based on system safety assessment methods extended within this investigation, it is also proposed in this investigation that indicators of producibility risk will stem from the evolution of governance. Consistency and effectiveness of control relative to the phase of product development must be considered to assess governance. This temporal alignment is significant as producibility risk is anchored in the earliest phases of product development, resulting in fixation of quality, product performance, cost, and schedule risk well before both the product configuration and operational structure have reached maturity. Traditional approaches to producibility management are unable to affect this early anchoring in the product development process. The significance of identifying new ways to manage producibility in early development is depicted in Figure 1-4 from the U.S. NAVAIR Producibility System Guidelines [1]. Configuration can be expected to lead the depicted fixed cost, thereby amplifying the importance of early producibility risk management.

It must be recognized that not all producibility risk can be eliminated prior to configuration and associated anchoring of baseline cost. While the included hypothesis suggests that traditional configuration-based producibility assessments have limited value, these methods

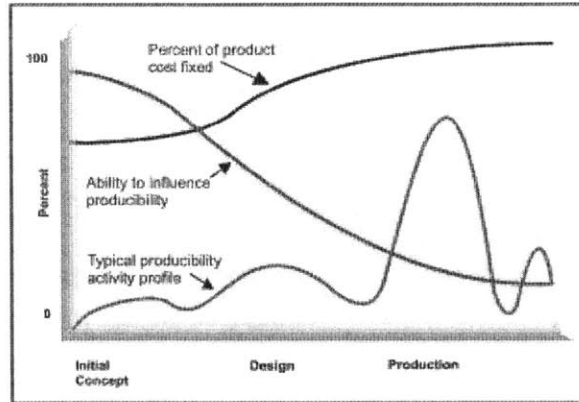


Figure 1-4: Temporal relationship between producibility influence and cost fixation in product development, along with a notional measure of traditional producibility management activity [1]

cannot be overlooked. New methods stemming from investigation of the organizational hypothesis must be integrated with known producibility management approaches, albeit the balance of applied resources may be adjusted. In addition, indicators associated with product complexity, product novelty, design standards, and process variation will be addressed in this investigation from the perspective of information flow within a product development organization. However, an extensive review of supporting design assumptions are left to investigations conducted previously by other authors. It is the expectation that value will be demonstrated in an blended approach to producibility risk management that is applicable not only to the case study entity, but the aerospace industry and any other large-scale, socio-technical product development system with a high level of organizational complexity.

1.5 Relevant Prior Institute Projects

A number of prior investigations initiated at the Massachusetts Institute of Technology (MIT) have examined organizational influence on aerospace risk in product development and product quality. While relevant academic literature will be reviewed as applicable in subsequent sections, a brief introduction for supporting MIT-specific initiatives is warranted to support continued evolution of research and methods.

The most directly applicable Institute initiative was the Lean Aerospace Initiative that

was conducted as a subset of the MIT Lean Advancement Initiative in the period from 1993 to 2013 [2]. This initiative was created to support a step in the evolution of manufacturing methods from the pioneering Toyota Production System in the late twentieth century to the Lean Enterprise. The notable change associated with this step was the introduction of new value creation methods for all organizational stakeholders beyond Operations to further promote waste reduction and improvements in cost, quality, and productivity [3]. The purpose of the Lean Aerospace Initiative was stated as to instigate, enable, and support an industrial revolution in aerospace production as significant as mass production.” The contributors to the initiative beyond MIT included large commercial and military aerospace manufacturers, NASA, the U.S. Army and Navy, the U.S. DoD, United Autoworkers, and International Association of Machinists [3]. Seven teams were defined within the initiative to look at all areas of aerospace production, inclusive of product development and organizational structure. The outcome of the initiative were models and roadmaps that supported a derived series of best practices for aligning an aerospace manufacturing system with the fundamental tenets of Lean Production [3].

A second MIT initiative related to this investigation is the Systems Engineering Advancement Research Initiative that is supporting continued development of System Engineering frameworks through the application of sociotechnical system methods. The research efforts are specifically focused on how system development phases operate in a dynamic social environment of high uncertainty [4]. Design risk and architecting systems for the -ilities, such as maintainability or producibility, are thrusts of recent research that complement this investigation. The goal of this initiative is to provide metrics, tools, and processes, that can be used to assess an organization in a dynamic environment and support a sustained level of organizational performance [4].

The final Institute initiative that supports this investigation is the MIT Partnership for a Systems Approach to Safety (PSAS) directed by Professor Nancy Leveson. The goal of the supporting team is to identify and validate new cross-disciplinary approaches to system safety that reflect the complexity and potential for loss within modern sociotechnical systems [5]. Specific areas pertinent to this investigation include new hazard analysis approaches and identification of leading indicators of risk. The initiative works across product and

process industries, militaries, and academia to aid in extensive identification of non-failure related mechanisms impacting organizational safety [5]. Extensions of methods from this initiative are being applied to non-manufacturing related applications and other emergent properties, a pursuit that this investigation hopes to further through method development for producibility.

1.6 Overview of Approach

The proposition that organizational structure and dynamics influence producibility risk to a greater extent than configuration within aerospace product development is systematically explored in subsequent sections within the framework of industry-representative Aerospace Corporation X product development and manufacturing operations. As assessment of organizational dynamics through a critical review of product development organizational structure and culture is first used to understand factors influencing the entire socio-technical system and adherence to producibility governance processes. A case study of a large product development effort within Aerospace Corporation X is then presented to quantitatively narrow the focus for assessment of producibility governance and sources of producibility risk in aerospace product development. From this case study, a detailed examination of producibility governance in product development is presented. Supporting this examination is development of an extension of System Theoretic Process Analysis (STPA), a hazard analysis technique from the system safety discipline, to provide a method for capturing the influence of sociotechnical system complexity on producibility risk. Examples of identified inadequate control and associated causation for Aerospace Corporation X are highlighted to provide the necessary foundation for producibility risk indicator identification.

From the producibility governance assessment, an STPA-based approach to risk management is presented with application to Aerospace Corporation X product development. The resulting risk indicators are used to develop a risk management framework. A combination of expert assessments and quality loss correlation is used to validate the relationship between developed risk management methods and producibility outcomes. This validation is also used to assess the validity of the presented proposition for organizational influence

on producibility risk. Finally, recommendations for operational data structures and analysis are provided to support comprehensive aerospace producibility risk management.

Chapter 2

Background and Literature Review

To perform the proposed investigation and develop a method for producibility risk indicator identification, a review of existing development and risk management practices in aerospace as they relate to both product definition and manufacturing is required. In addition, a fundamental understanding of how producibility is currently addressed in industry and background on hazard analysis techniques for socio-technical systems is required. This section presents a review of literature relevant to these topics to provide the necessary understanding for both subsequent organizational assessment and hazard analysis extension in producibility risk management.

2.1 Aerospace Product Development

The approach to product development in aerospace industries, often referred to as new product introduction or integrated product development, can vary significantly with the development organization, new vs. derivative products, military vs. commercial products, and even geographic regions and cultures. The intent of this literary review section is not to delve into all of these permutations of product development, but rather provide a succinct overview of general attributes of aerospace product development. The referenced literature can be used to support detailed examination of aerospace industry development methods.

2.1.1 Phased New Product Introduction

The aerospace product life-cycle typically spans multiple decades due to the level of customer investment and the pace of innovation. The associated product development effort tends to be proportionally as extensive with most development programs ranging from three years to a decade, with significant variability on the upper bound depending on the product. Commercial product development efforts tend to be shorter due to cyclical product market pressure, while military projects can range from shorter technology-proving activities to multiple decade, next generation products with associated intensive research. To accommodate the significant development duration, a regimented or phased approach to new product introduction is typically employed within all large aerospace product manufacturers. These incremental approaches help manage the level of organizational complexity and demands for short term results from financial markets. Focus is placed on stage-gate approaches in aerospace to support a description of the process in use at Aerospace Corporation X.

The stage-gate project management model defines a structured chronology from product conceptualization to product release to the market [6]. The key components are stages comprised of value-added activities and gates where decision-making and assessment occurs. A generic depiction of the model is presented in Figure 2-1, an adaptation of Coopers model by Johansson [7].

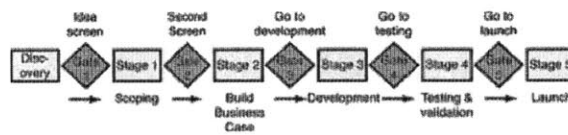


Fig. 1. Stage-gate process overview (adapted from Cooper [2008]).

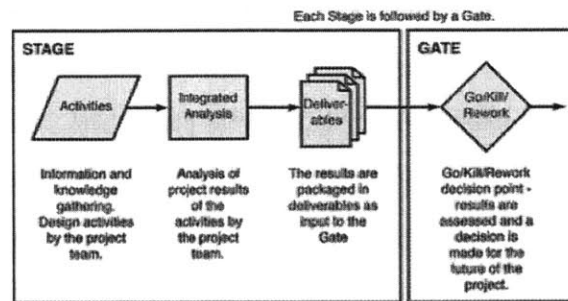


Figure 2-1: Depiction of generic stage-gate product development process with detail on stage vs. gate activities [7].

Gates are supported by a number of deliverables from project activities and decision processes, often simple checklists, or reviews that validate progress has been made to reach predefined criteria associated with a given gate. The phased review process was first implemented by NASA in the 1960s to address project challenges before they propagate, and allow for resource reallocation or project cancellation as required. Consistent with this purpose, the stage-gate approach is not only a way to manage the progress of development, but also incrementally assess risk. Johansson notes the types of gate deliverables can include the following [7]:

- Project assurance plan
- Design configuration data
- Technical reports and documentation
- Test reports
- Analyses reports
- Tacit knowledge

Johansson notes that while a lot of gate information can be provided, who is qualified to assesses fitness for purpose? Specifically, what is the readiness level of information, what is missing, and how do activities and resources get reallocated based on the information [7]? The stage-gate process flow and associated decision-making at gates must therefore not occur in a vacuum or with short term perspective.

On any project, specifically in a long term engagement such as aerospace product development, there are typically forming and restricting contracts between organizations. Formation of these contractual relationships early in the product development process creates a financial incentive in the stage gate process to reach a successful resolution at gates, even when compliance with gate criteria is debatable. A failure to move forward would incur contractual penalties within a supply chain or with a customer [8]. This detrimental incentive to long term perspective is coupled with the fact that product development involves uncertainty in the configuration, and often requirements, as well as communicating incomplete or approximate information [9]. The result is it becomes very difficult at the early gates, and even within associated stages, to manage risk against configuration and operational execution. Eisehart and Zbaracki noted its a situation of bounded rationality, where externalities cannot be controlled and outcomes may not be predictable, so people act with rationality within

what they know [10]. Externalities can be significant in aerospace due to the cyclical nature of the business and customers, as well as many unknowns in product creation due to product complexity. This is where development process governance and cross-functional integration become critical within an organization, and why emergent properties, such as producibility, can be at risk without any explicit failures or intentional lack of oversight.

Aerospace Corporation X employs a basic seven-step, stage-gate process for new and derivative product development programs, as shown in Figure 2-2.

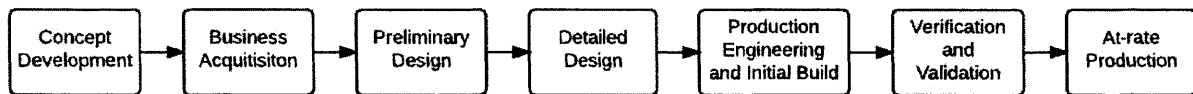


Figure 2-2: Aerospace Corporation X product development gated process

The initial phases of concept development and business acquisition can vary in their relationship, typically between parallel or series activity, depending on the nature of a given customer. For final validation and at-rate production, there is some variation between the phases between military and commercial products, but this is not pertinent to the investigation. Fundamentally, both the product and dedicated-processes mature from concept development through verification and validation to a point where known demand can be satisfied in at-rate production. In addition, the product development organization or programmatic governance matures throughout the process due to a steadily increasing scope of Engineering work and a need to support development of Operations.

2.1.2 Military vs. Commercial External Oversight

The prior section noted that some differences in military vs. commercial product development flow were not germane to this investigation. While this proposition holds for flow, there are unique aspects of external aerospace industry governance, specifically with regards to the customer and regulatory involvement, that must be noted to facilitate analysis of producibility risk drivers in this investigation.

In commercial air vehicle product development, unique external governance takes the form of regulatory certification of three aspects of a product program: the air vehicle type, the product system, and product airworthiness. Customer oversight may be present in some

programs through a sales and marketing interface, but it is not a prime driver of producibility. The regulatory oversight occurs in parallel with product development, starting from early product configuration through certification and into at-rate production. U.S. government oversight through the Federal Aviation Administration (FAA) office of the Department of Transportation is broken down into the five following phases [11]: conceptual design, requirements definition, compliance planning, implementation, and post-certification. Product compliance with requirements and quality, two primary drivers of producibility are shaped by this oversight process.

In the conceptual design phase, really occurring during the preliminary design phase of the organization, general product familiarization and regulatory guidance-directed selection of a statutory certification basis is provided by the aerospace manufacturer [11]. The resultant producibility impact occurs through the fixation of statutory requirements, a certification basis, that will drive product performance and the level of validation effort, as well as cost and schedule. The next phase of requirements definition requires the applicant for certification, or product manufacturer, to provide more detailed design and process planning data, along with proposed schedules, to support building of an integrated project plan with the FAA and identification of regulatory areas of interest. Part of the design planning data includes a safety analysis that will determine where additional regulatory guidance or introspection, a driver of statement of work in product development, will be required. The third phase requires a detailed definition of how the applicant will show compliance with the applicable regulations and guidance provided under the selected certification basis for the type design. It also requires a refined assessment of system safety and a description of controlled production processes [11]. While fixing requirements for product performance and verification, this point in the process is notable for the initiation of certification of the production system and inherent quality system that will be used for the initial product build.

The fourth phase, implementation, requires submittal of all validating analyses, initial article inspections, and a final safety analysis to support type design approval [11]. This phase includes an audit of the production system to ensure that the quality plans presented provide repeatable units that are consistent with the type design and stated safety standards. It is also a critical point for producibility, as the aggregation of product performance, quality,

and schedule is being assessed late in the development cycle. Finally, the last phase is the post-certification phase during which ongoing configuration management and product performance are assessed, along with the airworthiness of each produced unit for delivery to customers [11]. Producibility impacts of this phase are relatively insignificant compared to the effect of prior program oversight activities. In summary, the regulatory oversight for commercial aerospace air vehicles involves continuous external oversight with discrete touch points integrated into most of the stage-gate product development phases. Consideration for the impact of certification requirements on new product development must not be overlooked as an external governance mechanism, given the potential for impacts on product performance, quality, cost, and schedule.

Military product development invokes an even greater level of oversight during the development process, but this time occurring through the customers constituent organizations. Given the focus on U.S. military sales at Aerospace Corporation X, U.S. government oversight is considered as a model for military customer governance. The increased scrutiny associated with military customer oversight is the result of not only the scale of the customer military organization, having integral engineering and project management functions, but also the fact that product development of military vehicles is a subset of the overall defense acquisition process for a specific capability. The U.S. DoD generic acquisition process can best be explained from the visual presentation of phases and decision points in Figure 2-3.

The U.S. military acquisition process invokes a series of Milestones which are major program decision points and also correspond to financial disbursements to industry manufacturers. These milestones have a disproportionate prioritization over manufacturer stage-gates in relation to internal development governance due to the associated capital implications. Unfortunately, this prioritization supports short term perspective at various stages of a product development program to ensure all criteria are met to receive the next funding disbursement. Similar to internal stage-gate processes, this program management incentive must be considered with regards to governance of risk management decisions.

In detail, the acquisition process starts with an analysis of solutions for strategic needs and programmatic risk reduction activities before significant industry engagement. Subse-

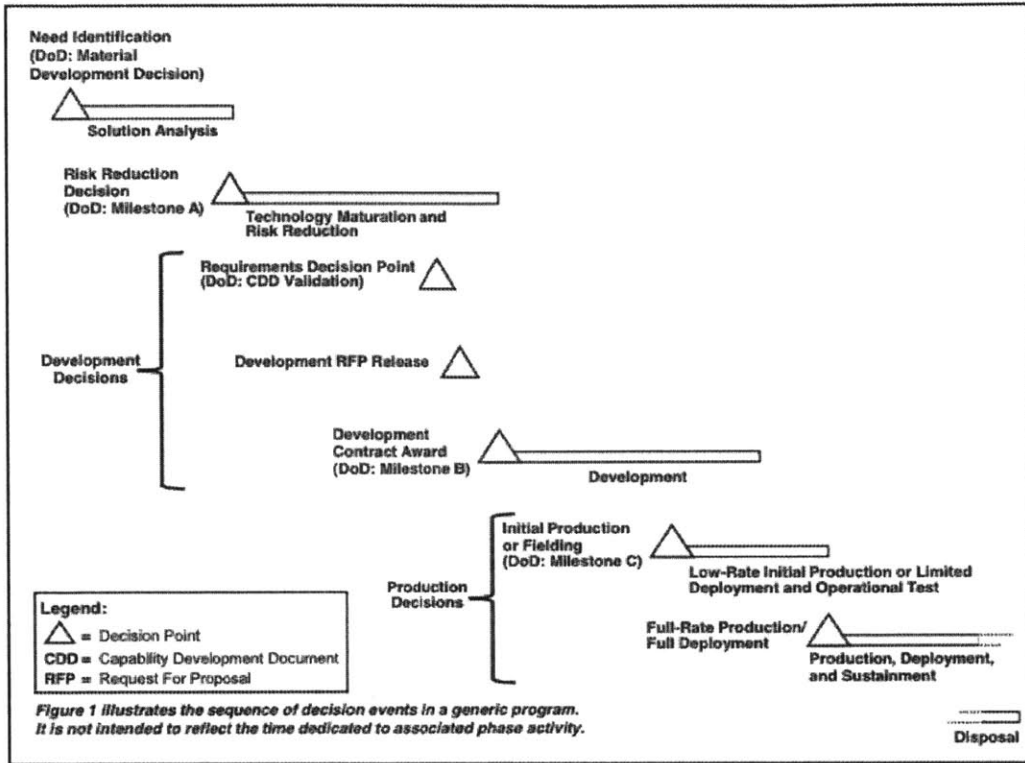


Figure 2-3: U.S. DoD acquisition process phases and decision points [12]

quent technology and risk reduction work is pursued with a down-selected pool of industry partners before release of official Tier I requirements and the request for proposal (RFP). This early establishment of relationships supports risk reduction, but it also allows industry partners to influence requirements to reflect their assumed product and process capability. An incentive is introduced to tolerate uncertainty in capability due to the need to project competitive capability for contractual opportunity. The DoD technical oversight authority provides support to the DoD program office to try and assess manufacturer capability, but access is not possible to the same extent as in later phases of the program due to outstanding contract awards. Focus needs to be placed by both parties on producibility risk at this stage to avoid untenable product capability and performance.

Once an industry partner has been down-selected, the military customer is much more engaged in the stage-gate process, from preliminary design forward. While beneficial for additional technical oversight and review, the level of customer engagement means there is more introspection before open acknowledgment of risk. In addition, the focus on demon-

strating progress to the integrated customer may contribute to an inability to adequately assess risk for emergent properties, such as producibility. The incentive suppositions made here are not matter of fact, but must be addressed when assessing producibility governance in a military product environment.

2.1.3 Measuring Development Program Performance

The standard approach to aerospace product development has been presented as stage-gate, and influential external oversight has been discussed, but internal methods of measuring product development program performance at each gate need to be understood to support governance process understanding. Identifying metrics reflecting program and product development performance are complicated by the complexity of the involved socio-technical systems, the size of organizations, and the ability to collect non-biased data across different functions. As noted by Brown and Eisenhardt, any assessment must simultaneously measure the health of the product development process itself, the maturity of the product, and financial performance stemming from the first two aspects [13].

Given the difficulty in selecting performance parameters, most aerospace product development efforts boil performance down to measurement of statement of work completion per a previously defined development schedule and a measure of cost [14]. For modern development programs, the Earned Value Management System (EVMS) is often used to aggregate these basic measures with project management statement of work. EVMS uses financial feedback of either labor hours or non-recurring cost to calculate metrics of work completed, work remaining, cost of work performed, and estimated cost remaining in relation to planned cost. Two of the most common resultant EVMS measures are the cost performance index (CPI) and schedule performance index (SPI), which will be discussed in greater detail in the included case study. These basic program metrics are coupled with product performance measures specified by internal System Engineering and customer specifications, such as range, payload, fuel consumption and similar metrics. The set of metrics is then usually group into key performance parameters and technical performance depending on the level of validation required by the customer. Beauregard et. al. provides a succinct list of measures in practice in Table 2-1 from an aerospace case study company while noting commonality

across the industry [15].

Table 2.1: Common product development program metrics [15]

<i>Metric</i>	<i>Description</i>
NPI effectiveness index	Ratio of the total value of engineering output to cost of the engineering department
Compliance to customer requirements	Ratio of total number of non-compliances to total number of requirements
Schedule performance earned value index (PMI, 2013)	Ratio of budgeted cost of work performed over budgeted cost of work scheduled
Cost Performance Index (PMI, 2013)	Ratio of budgeted cost of work performed over actual cost of work performed
Late design changes	Ratio of the number of design changes post-release to manufacturing over the total number of design changes
Changes not driven by the customer	Ratio of design changes due to specification change or company error over the total number of design changes post-critical design review or release to manufacture
Information inventory efficiency	Ratio of the number of new parts on the bill of materials over the total number of parts on the bill of materials
Engineering throughput	Ratio of number of milestones completed for a project over the project man-hours expended

Beyond the basic program metrics and product performance measures, there are few standardized approaches in practice for assessing other aspects of development program health such as capability and productivity prior to low-rate production. A review of Table 2-1 shows that all of the metrics relate back to cost and schedule, or occur later in a program during detail design or initial production, allowing for only reactionary mitigation of problems incurred much earlier in the product development program. Program managers typically try to deduce a suite of metrics for earlier program health assessment, but often find these metrics are not robust enough to ensure consistent reporting or correlation to predicted outcomes, thus resolving themselves back to the basic and reactive measures of cost and schedule performance-to-plan. Academic efforts to fill this gap have been prevalent but tend to focus on quantitative approaches to one of the aspects of product development programs, such as process, product configuration, or financial risk management. The framework by Song and Montoya-Weiss for product development process performance is just one example [16]. Beauregard is an exception by presenting the list of broader system engineering metrics in Table 2-2 for aerospace product development with an attempt to validate the lean nature

of a case study product development effort [15].

Table 2.2: Proposed product development metrics by Beauregard [15]

<i>Metrics</i>
Requirement trend maturity against plan
System definition change backlog trend
Interface specification closure against plan
Requirements verification and validation trend
Work product approval trend
Action closure trend
Risk exposure trend
Risk handling trend
Technology maturity trend
Technical measurement trend
System engineering staffing and skills trend
Process compliance trend

In addition to not having all the necessary operational data, Beauregard’s metric development is focused mostly on Engineering-only aspects of product development. Systematic development of broader metrics is needed to assess the health of practices that support successful product development, namely cross-functional integration, experience, communication, project planning, working level gatekeepers, and effective leadership [17]. These metrics must also be able to support effective risk management system implementation and development.

2.1.4 Configuration Control

Management of change in both product configuration and production system processes is an obvious area of influence on producibility. Due to the complexity of aerospace products, the necessary condition of safe operation, and the associated level of external oversight, configuration change control tends to be an area with rigorous oversight in product development organizations. Unfortunately the rigor often detracts resources and focus away from ongoing risk management and communication needed to stem further losses of producibility, which can drive additional change. This section provides a brief overview of factors influencing aerospace product configuration management mechanisms to support understanding

of coincident effects on producibility governance.

Configuration management is critical both in new aerospace product development and change to products currently in production. A general definition of configuration management is a management process for establishing and maintaining consistency of a products performance, functional, and physical attributes with its requirements, design and operational information throughout its life [18]. It is central to both having a marketable product and management of operating performance. Even with the noted criticality, the aerospace industry continues to struggle with change management [19]. From a product development perspective, change management traditionally makes its value evident when multiple changes are required after a configuration is designed to either meet performance or quality requirements, and these changes must be aggregated into a final configuration for at-rate production [19]. While focus on schedule and cost can incentivize limited effort expenditure, effective change management requires rigorous record retention and decision-review processes to ensure there is no loss of configuration information. Recent decades have seen an increased use of information technology (IT) to facilitate integrated change management [20], although a majority of aerospace organizations noted in 2005 that IT was still inadequate for a comprehensive configuration management system. Companies also indicated a high level of uniqueness in configuration management approaches even though there are industry standards driving the foundations for processes [20]. While exploration of the array of change management approaches is out of scope, Ali and Kidd did present aggregated reviews of literature to highlight attributes associated with successful and unsuccessful change management process implementation. These attributes are presented respectively in Table 2.3 and 2.4 [21].

The configuration management factors identified in Table 2.3 and 2.4 need to be considered when assessing producibility governance. The factors also need to be examined from a temporal perspective, given ineffective dissemination of change for approval or implementation can amplify producibility losses. Specific areas of change management influence will be examined in the subsequent case study supporting this investigation.

Table 2.3: Literature-identified factors for successful configuration management [21]

Key important factors	References
Management support	Samaras (1988), MIL-HDBK-61 (1997), Guess (2006)
CM specialists, simplest CM process	Samaras (1988)
Good standards	Hancock (1993), MIL-HDBK-61 (1997), Guess (2006)
CM planning	Guess (2006), Sachs (2009)
Efficient software tool	Fowler (1993), Guess (2006)
Effective communication	Tavcar and Duhovnik (2005), Yeh and Tai-Hsi (2005), Guess (2006), Jarratt <i>et al.</i> (2011), Wasmer <i>et al.</i> (2011)
Proper resources allocation	MIL-HDBK-61 (1997), Gonzalez and Zaalouk (1997), Guess (2006)
Training	Samaras (1988), Hancock (1993), Gonzalez and Zaalouk (1997), Guess (2006)
Cooperation	Samaras (1988), MIL-HDBK-61 (1997), Gonzalez and Zaalouk (1997), Guess (2006), Jarratt <i>et al.</i> (2011)
Good leader	Guess (2006), Watts (2008)
Team work	Sachs (2007)
Creative and committed professional	Sachs (2010)
Continuous improvement	Hancock (1993), Guess (2006)

Table 2.4: Literature identified detractors impairing configuration management [21]

Failure factors	References
Lack of management support	Gonzalez and Zaalouk (1997), Burgess <i>et al.</i> (2005)
Lack of CM training	Burgess <i>et al.</i> (2005)
No clear career paths for CM personnel	Burgess <i>et al.</i> (2005)
Lack of resources	Gonzalez and Zaalouk (1997)
Lack of standardization	Gonzalez and Zaalouk (1997)
Lack in users acceptance	Fowler (1993), Gonzalez and Zaalouk (1997)
Lack of continuous improvements strategies	Gonzalez and Zaalouk (1997)
Lack of communication, coordination and cooperation	Jarratt <i>et al.</i> (2011)

2.2 Quality in Product Design

Quality is arguably the most important factor in producibility, as its impairment can drive a reinforcing effect on producibility loss through the attributes of cost, schedule, and product compliance. As a critical factor, a brief treatment is needed to understand how quality can impact the product development process in aerospace and when quality is usually integrated into producibility governance. This background will help with assessment of quality mechanisms in Aerospace Corporation X product development and the role of quality in the definition of leading indicators for producibility risk.

All aerospace manufacturers employ a quality management system, typically stemming

from ISO 9001 or AS 9100 standards, as it is necessary not only to achieve regulatory approval, but also to deliver a safe and reliable product. The question for firms is therefore not how to govern quality, but how to use the resultant measures of quality to improve operating performance and product development. From this perspective, there is great variation between manufacturers in the industry. In addition, the Design Engineering function has traditionally lagged behind Operations in both awareness and improvement of quality [22]. Quality in aerospace manufacturing is usually assessed by the relative number of non-conformances in the physically manifested product in relation to the defining configuration data and specifications. Given the relatively slow rate of production, quality implementation in aerospace typically invokes inspection and tool calibration, supplemented by other forms of product testing or measurement for key components and systems. The lack of high-rate production coupled with the unique configuration for each product type have resulted in limited penetration of statistical process control methods that provide the ability to reference quantitative process capability. In addition, only in recent decades has quality been extended outside of production operations to areas such as Engineering and Supplier Management for items such as design data or requirements, respectively.

There have been two significant drawbacks that have resulted from the narrow quality focus within aerospace organizations. The first and most straightforward is that there is a lack of understanding within the organization of how to integrate quality across disciplines. Beyond the obvious importance of cross-functional integration in defining unified requirements, studies have pointed to characteristics of cross-team interactions and context as being significant to quality outcomes for new products. Interaction characteristics have to do with formal and informal linking between the groups. Context has to do with programmatic constraints placed upon team and customer influence [23]. The relationships between functional disciplines and product requirement dissemination are therefore critical determinants of product quality. The second drawback is the lack of process data and characterization to help disciplines removed from Operations understand capability. Most important is lack of information about uncertainty and sources of variability that can help in early product configuration. This information not only helps in defining configuration to match processes, but also in understanding of cost reduction opportunities and anticipated

reliability problems for systems and materials [24]. Together, there is a significant amount of influence on producibility that is overlooked in the current quality management approach within most aerospace organizations. The result is design changes late in the product development process that not only reduce producibility as exemplified in Figure 2-4, but reinforce future producibility impairment due to resource commitments required for mitigation.

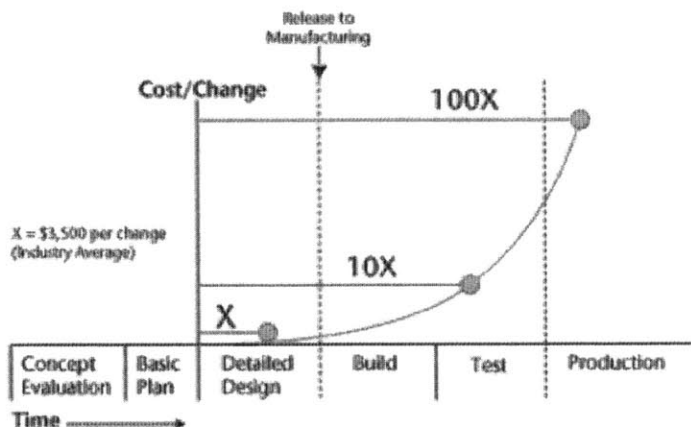


Figure 2-4: Expected cost behavior for configuration changes over the course of an aerospace product development program. [22]

Producibility risk assessment must examine the organization for the noted process data omissions and highlight indicators that relate to missing quality information. Assessment must also involve looking for relationships that drive process repeatability, mature engineering information, interoperable data, and knowledge retention [22].

2.3 Manufacturing Readiness Assessment

Understanding that producibility must be addressed earlier in product development is not a foreign concept to modern aerospace manufacturers, but effective methods besides expert oversight at gate reviews have yet to become standardized. One supporting approach that is gaining traction is meant to focus on the integration of Manufacturing Operations with the Engineering organization and stems from military acquisition program oversight and technology development. The concept, manufacturing readiness level (MRL), is a direct copy of the already extensively used technology readiness level (TRL) framework. The associated

methods involve conduct of assessments designed to identify transition to build and manufacturing risk using a standardized attribute maturity scale. The goals are to define the current level of manufacturing maturity, identify maturity shortfalls along with associated costs and risks, and provision for manufacturing risk management [25]. The approach was developed by military and industry working groups for the U.S. DoD in response to a government accountability office report that stated a lack of manufacturing knowledge was the primary driver of cost overruns and schedule delays in new product acquisition programs [26].

While associated with risk management, the MRL methods are specifically designed to support discrete periods of oversight at either company gates or acquisition milestones. The basic approach is to first conduct assessments of manufacturing and process maturity for nine threads, or categories, and associated sub-threads in relation to a provided reference scales. Subsequently, scores are given for proven capability at the sub-thread level on a scale from one to ten. These scores correspond to maturity of the product system with the following definitions [25]:

MRL 1: Basic manufacturing implications identified

MRL 2: Manufacturing concepts identified

MRL 3: Manufacturing proof of concept developed

MRL 4: Capability to produce technology in a laboratory environment

MRL 5: Capability to produce prototype components in a production relevant env.

MRL 6: Capability to produce a prototype system in a production relevant env.

MRL 7: Capability to produce systems or components in a production relevant env.

MRL 8: Pilot line capability demonstrated; begin low rate initial production

MRL 9: Low rate production demonstrated; capability in place for full rate production

MRL 10: Full rate production demonstrated and lean practices in place

Note: After scoring across all sub-threads, the lowest score is identified and used as an assessment of readiness level of the manufacturing system for a given product program.

The scoring system is simple in its approach but provides a valuable framework to drive cross-functional conversation about manufacturing capability and evidence-based risk mitigation. The methods are just beginning to be adopted on new military product programs in the industry so further assessment will be required to determine efficacy for mitigating producibility risk. There is an inherent limitation in the experience-based criteria in this

approach, in that assessments and risk identification become more challenging for implementation of unique product configurations with new or modified manufacturing processes. The evidence basis incentivizes a trial and error manufacturing approach without assessing the integration of the design with capability. Evolution of this technique is also needed to incorporate design aspects beyond technology readiness or complementary methods such as the one proposed in this investigation need to be considered.

2.4 Measuring and Controlling Producibility

Producibility is an emergent property stemming from quality, product compliance with requirements, cost, and schedule for product development or sustaining production operations. It is focused on the relative ease of manufacturing a product within a given set of constraints [1]. As an emergent property, it is difficult to both quantify and control. Methods for managing each of its constituent elements in aerospace product development are numerous and each organization molds industry best practices into their own standard work though a juxtaposition with product and financial market strategy. Assessment of producibility in aggregate is a relatively new concept for commercial aerospace products, with some prior investigation for military products through U.S. DoD-sponsored research initiatives. This section provides a brief introduction to what techniques exist for measuring and controlling producibility. Familiarity will allow for comparison to proposed methods and integration of configuration-based principles into an integrated producibility risk management framework.

The bulk of available research on assessing producibility and managing risk is focused around either assessment of product features with respect to demonstrated manufacturing processes or managing quality nonconformance. Assessment of product features and associated design processes from the perspective of manufacturing process capability is the same approach used in Design for Manufacturing (DfM) and Design for Assembly (DfA) methods. Extensive research has been done in these areas to facilitate the product transition to build stage and a number of heuristic, algorithmic, and rule-based systems have been developed to assess and guide product configuration. Aurand et al. provides a comprehensive summary of automated approaches to DfM along with their required level of detail, development phase

of implementation, and associated indices as shown in Table 2.5 [27]. With a similar goal of affecting design earlier when risk can be mitigated, Aurand et. al. also explored empirical and objective design-rating systems. Summaries of these approaches are presented in Tables 2.6 and 2.7. Most of the listed techniques are not capable of examining concept or early designs, with partially specified configuration, in the product development environment. The one technique that is capable from McLeod is the producibility assessment worksheet (PAW). This technique has been used at Aerospace Corporation X but is limited by the knowledge of the individual product designers and provides no relation to an organizational risk management system or program constraints. In response to the method review, Aurand et al. presents a method for an earlier producibility assessment titled hierarchical evaluation method for earlier design (HEMED) [27]. This method benefits from encapsulation of known production outcomes from product configuration and levels of utility based on design objectives. The method is demonstrated to be preferential over the PAW approach but it is still product design-centric. It lacks flexibility in its automated nature to adjust to the various levels of program maturity, as well as capture organizational attributes of production operations and business operations. Its rigidity, which is meant to instill control, limits application in organizational governance for producibility.

Table 2.5: Design for manufacturing automated method research summary [27]

Author(s)	Year	Domain	Design form	Earliest LC phase				Production feasibility?	Indices
				CD	ED	DD	PP		
Vaghul <i>et al.</i>	1985	Inj. Mold	Mfg. Features			X		Yes	
Luby <i>et al.</i>	1986	Casting	Mfg. Features			X		Yes	Material usage efficiency
Swift <i>et al.</i>	1986	Coatings	Mfg. Features			X		Yes	
Kim <i>et al.</i>	1988	Turning	Mfg. Features			X		Yes	
Lu and Subramanyam	1988	Turning	Mfg. Features			X		Yes	
El-Gizawy <i>et al.</i>	1989	Forging	Process Plan				X	Yes	
Ranta <i>et al.</i>	1989	Milling	Mfg. Features & Process plan				X	Yes	
Schmitz and Desa	1989	Stamping	Mfg. Features			X		Yes	Cost
Colton and Dascanio	1990	Milling	Mfg. Features			X		Yes	
Shah <i>et al.</i>	1990	Milling	Mfg. Features			X		Yes	Cost
Ulrich and Graham	1990	Forming	Mfg. Features			X		Yes	
Wade and Colton	1990	Milling	Mfg. Features			X		Yes	
You <i>et al.</i>	1990	Casting	Mfg. Features			X		Yes	
Anjanappa <i>et al.</i>	1991	Milling	Mfg. Features			X		Yes	
Gadh <i>et al.</i>	1991	Plastic Injection	Mfg. Features			X		Yes	
Adalier and Tsatsoulis	1992	Milling	Mfg. Features			X		Yes	
Hilbert	1992	PC Boards	Mfg. Features			X		Yes	
Pudhy and Dwivedi	1992	PC Boards	Mfg. Features			X		Yes	
Rosen <i>et al.</i>	1992	Casting	Mfg. Features			X		Yes	Cost
Sanchez <i>et al.</i>	1992	Milling	Mfg. Features			X		Yes	
Schmitz and Desa	1992	Stamping	Mfg. Features			X		Yes	Cost
Shivaram and Naganathan	1992	Stamping	Mfg. Features			X		Yes	

Table 2.6: Empirically-based design assessment methods for early producibility management [27]

Author(s)	Year	Domain	Design form	Earliest LC phase				Production feasibility?	Indices
				CD	ED	DD	PP		
Adler and Ishii	1989	Assembly	Mfg. Features			X		Yes	Match Index S.E. Index
McLeod	1989	General	Part Drawings	X				No	Probability of Success
Sanchez and Priest	1990	Milling	Part Drawings			X		No	Mfg. Index
Priest and Sanchez	1991	General	Part Drawings			X		No	Prod. Index

Table 2.7: Objective design assessment methods for early producibility management [27]

Author(s)	Year	Domain	Design form	Earliest LC phase				Production feasibility?	Indices
				CD	ED	DD	PP		
Harry	1989	Electronics	Process plan				X	No	Yield
Hayes <i>et al.</i>	1989	Milling	Process plan				X	No	Number of setups
Allen and Swift	1990	General	Mfg. Features		X			Yes	Cost
Heng and Gay	1991	PC Boards	Mfg. Features		X			Yes	Cost
Poli <i>et al.</i>	1991	Stamping	Mfg. Features		X			Yes	Die Cost
Yannoulakis <i>et al.</i>	1991	Turning	Mfg. Features		X			Yes	Machining time Number of tool changes Feature machinability Manufacturability indicator

As with the presented product feature-based approaches to producibility management, quality-based approaches exhibit difficulty in assessing the organizational aspects of producibility early in the product development cycle. The majority of these methods are derived from the DMAIC approaches of Six Sigma quality control. An example from Rumpf *et al.* reviews the General Electric process of gathering product features that are either critical to quality or defined key characteristics, and assessing the tolerances on those features with respect to the known variability in fabrication and assembly processes [28]. The method review notes that "the process of evaluating every characteristic identifies producibility problems early in the design process." There is a follow-on discussion presented on how to structure the organization and conduct pre-production reviews to highlight producibility risk, but it assumes adequate product configuration is available at the time of assessment [28]. More attention is needed on knowledge management and design controls to ensure that the first iteration of the detailed design reflects process capability, as defined from organizational and quality assessments. This will be achieved through design phase governance that promotes knowledge retention, application, and exchange [29]. The goal for the design process is best

reflected in the visual progression depicted in Figure 2-5.

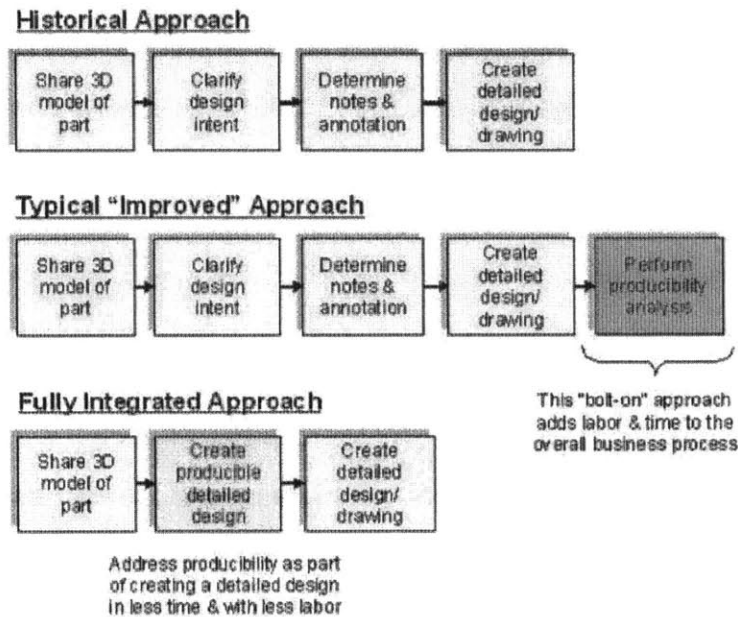


Figure 2-5: Progression of product development practice to achieve producibility on the first iteration of configuration within Engineering [29]

One of the most comprehensive examinations of how to integrate producibility assessment and control with a design and manufacturing program was conducted by a military-industrial-academic producibility task force and documented in a U.S. Navy specification in 1999 [1]. This specification outlines the following five integrated steps for a successful producibility program:

1. Establish a producibility infrastructure
2. Determine process capability
3. Address producibility during conceptual design
4. Address producibility during detailed design
5. Measure producibility

Details of how to implement each of these steps are provided in Figure 2-6.

Producibility Steps and Elements	Product Phase			
	Initial Concept	Preliminary Design	Detailed Design	Production
Step 1 - Establish a Producibility Infrastructure				
1.1 Recognize the Need for Management Commitment	X	•	•	•
1.2 Organize for Producibility	X	•	•	•
1.3 Implement a Risk Management Program	X	•	•	
1.4 Incorporate Producibility into New Product Introduction Strategy	X			
1.5 Employ Producibility Design Guidelines		X	•	
1.6 Instill a Commercial Best Practices Philosophy	X	•	•	•
Step 2 - Determine Process Capability				
2.1 Understand Current Process Capabilities (Company and Supplier)	X	•	•	•
2.2 Predict Future Process Capabilities		X	•	•
Step 3 - Address Producibility During Conceptual Design				
3.1 Identify Product Goals	X	•		
3.2 Identify Key Characteristics	X	•	•	
3.3 Perform Trade Studies on Alternative Product and Process Designs		X	•	
3.4 Develop a Manufacturing Plan		X	•	•
3.5 Perform a Complexity Analysis		X	•	
Step 4 - Address Producibility During Detailed Design				
4.1 Conduct Producibility Engineering Review			X	
4.2 Error-Proof the Design			X	
4.3 Optimize Manufacturing			X	•
Step 5 - Measure Producibility				
5.1 Measure Processes	X	•	•	•
5.2 Measure Products				X
5.3 Measure Producibility System				X

X - denotes the phase in which implementation of the producibility element begins
• - denotes continuing implementation of the producibility element

Figure 2-6: Practices from producibility system specification NAVSO P-3687 [1]

The steps in Figure 2-6 go well beyond product configuration into organizational design and socio-technical management. The methods included in this investigation attempt to complement existing tools and processes that support conduct of the steps presented in the Navy specification. The included risk framework also attempts to encapsulate the Navy framework in a manner tailored for governance of producibility within a specific organization. The goal is to support consequence assessment for organization-specific impacts of impaired producibility early in product design.

2.5 Identifying and Managing Integrated Program Risk

The U.S. DoD defines risk as a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule, and performance constraints [1]. Capturing and mitigating risk as early as possible in the product development cycle is therefore not only desired, but critical to achieving a desired level of producibility. To be effective in risk management, risk management programs must be planned with early identification of risks in development, early mitigating action taken, continuous monitoring, and

open communication [45]. This section presents a succinct overview of standard aerospace risk management methods for product development to identify integration points for the new risk management approach for producibility developed in this investigation.

Risk management takes two forms on aerospace product development programs, product and financial risk. While intimately related, they are often managed separately due to the functional isolation between Engineering and Business Operations. Traditional methods of assessing financial risk involve study of variance in return on investment often with a coincident measurement of expected product utility. The goal is to update projected net present values of investment projects and achieve efficient risk-return frontiers for project portfolios. Cox presents an analysis that shows that decision-making based on mean financial return with an expected variances in not in line with principles of a rationale decision-maker and therefore may not be the best approach for large-scale, high investment projects [46]. Inline with this concern, aerospace organizations have transitioned financial risk management models for development products to follow the format used in management of technical risk.

Industry standard groups, government regulating bodies, government standard organizations, and private institutes have all defined variations on risk management systems used in the aerospace industry but common threads exist between the methods. A singular technical risk management approach for aerospace will be reviewed with the understanding. While the International Standards Organization (ISO) standard 31000 is broadly applied in general industry, the U.S. DoD standard for risk management in acquisitions will be outlined due to an aerospace focus. From the DoD standard, the risk management process can broken down into the following five high-level activities [45]:

- Risk Identification
- Risk Analysis
- Risk Mitigation Planning
- Risk Mitigation Plan Implementation
- Risk Tracking (or Monitoring)

These activities are depicted in the standard as a waterfall progression with the risk monitoring step allowing for re-initiation of the risk management process as issues or inadequate risk coverage are realized. The intent of the risk management framework is to support product life-cycle risk assessments through continuous risk management practice [45].

The first activity of risk identification is the basic task of establishing an organization for risk assessment and leveraging this organization to understand what potential shortfalls to development program or product requirements may exist. Ideally, identification occurs through program and product decomposition either based on the statement of work or product functionality. Risks are traditionally identified through informal methods such as brainstorming or experience, or from formal technical assessments such as the hazard analysis techniques outlined in the following section. With risks identified, risk analysis is undertaken to explore qualitative root causes of risk and initiate risk reporting. Again, technical root causes can stem from the subsequently presented hazard analysis techniques but more variation exists in the methods used for qualitative identification of socio-technical or organizational system risk. Extensive review of employed methods is not germane to this investigation but the reader is referred to the Cox text on risk analysis in complex systems [46] for technical risk analysis and the Project Management Body of Knowledge [47] for development organization risk analysis. With an initial understanding of root cause, risk reporting is initiated by assigning a likelihood and consequence of occurrence to the identified risk. While likelihood is generally based on an assessment of probability, organizations usually develop their own criteria for consequence assignment that reflect technical, schedule, or cost performance thresholds [45]. In essence, consequences identify the expected level of producibility for risk realization. With assignment of likelihood and consequence, reporting is usually simplified using a colored risk matrix as shown in Figure 2-7 with levels of one through five corresponding to both increasing likelihood and increasingly unfavorable consequences.

While projected consequences can be quantified based on the financial or schedule impacts for a given risk realization, estimation of likelihood for future events is not straightforward due to historical bases for estimate having questionable applicability to development efforts [43]. Selection of probabilistic values corresponding to likelihood levels is usually based on experience or group think, which is readily biased. Opportunities therefore exist in practice for direct extension of risk identification to likelihood of occurrence, something that will be addressed as part of the hazard analysis extension in this investigation.

The remaining risk management activities focus on mitigation and monitoring to prevent

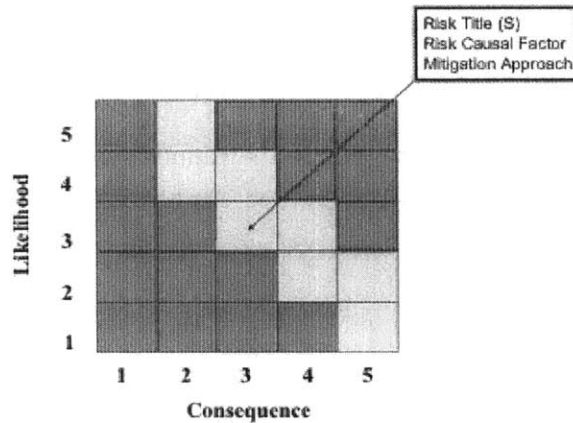


Figure 2-7: Risk reporting matrix typical to aerospace product development [45]

risk realization. Good risk management planning involves not only definition of what mitigating actions should be taken, but also when mitigation activities have to be accomplished, who is responsible, and what resources are required [45]. Given there may be multiple mitigation approaches with opportunity trade-offs, systematic risk mitigation planning is typically invoked in organizations through documentation and automated mitigation tracking. Tracking supports stage-gate reviews, but may be required more frequently based on dynamic information resulting from product and organizational maturation. The key to effective tracking is to have indicating metrics that are not only applicable over the duration of a given program effort, but also that yields early warning of increasing likelihood or severity in consequences [45]. The risk management process is iterative but indicators should be robust to changes in risk level and have the following attributes [43]:

- Complete
- Consistent
- Effective
- Traceable
- Minimal
- Continually improving and unbiased

In addition, a robust monitoring and management structure is needed for effective risk management. The organization must be responsive to the information provided through risk reporting and risk indicators, with established communication channels and triggers for risk action or re-assessment [43].

Implementation of a structured risk management program as outlined is a necessary but not sufficient step to effectively manage both product and organizational risk in aerospace product development. Both bias, as previously mentioned, and the uncertainties associated with quantitative vs. qualitative assessments for future events within an organization need to be understood to improve risk management outcomes. Leveson notes the following types of bias must be addressed through use of systematic frameworks in identifying hazards and assessing risks [43]:

- Confirmation bias
- Availability heuristic
- Recall of historical events
- Cumulative cause prediction
- Incomplete causal search
- Defensive avoidance

These biases can be compounded with cultural and political influences to drive error into likelihood and vulnerability assessment in the risk management process [43]. With regards to quantitative vs. qualitative analysis, extensive literature is available debating the merits of each approach and potential anchoring that occur in socio-technical systems thereby resulting in heuristic errors. While a comparative review is not warranted for this investigation, the reader is referred to Cox [46] and Rae et. al [48] for arguments supporting and opposing the use of quantitative assessment of risk as part of organizational risk management processes.

2.6 Hazard Analysis Techniques and Extensions

Methods developed as part of this investigation of producibility risk management leverage recently developed hazard analysis techniques stemming from system engineering and control theory. While hazard analysis is traditionally used to evaluate potential sources of safety loss, the methods provide a robust and systematic way of assessing causality for undesirable outcomes in complex systems, inclusive of social and technical elements.

This section provides a brief overview of traditional, reliability method-based hazard analysis techniques like failure modes and effects analysis (FMEA) and fault tree analysis (FTA), as well as other techniques like hazard and operability analysis (HAZOP) and fault

hazard analysis (FHA). These methods are contrasted with the more recently developed hazard analysis method of system-theoretic process analysis (STPA) selected for the basis of methods in this investigation. A brief introduction to the STPA framework is then provided along with a review of existing extensions of this method beyond system safety. Finally, the use of STPA for risk leading indicator identification is outlined to support subsequent producibility governance assessments.

2.6.1 Reliability-based Hazard Assessment Methods

A hazard can be defined as an undesired state of a system, that along with a set of environmental conditions, can lead to a loss. As Leveson iterates, hazards are not the same as failures and therefore hazards can be present with or without associated failures [31]. Ironically, traditional hazard analysis stemming from reliability analyses is based on the principle that system losses result from individual constituent element failures or an interaction of elemental failures. Reliability-based hazard assessments can be top down, from an undesirable loss or event, or bottom-up from the individual component failures. They also can be quantitative or qualitative in outcomes, lending to different opportunities for integration in a risk management process. The common bond is that these methods invoke a linear model of failure propagation based on a chain-of-events mental model. Failure modes and effects analysis (FMEA) and fault tree analysis (FTA) are the two most common implementations of reliability-based hazard analysis.

FMEA, and the related technique of Failure Modes, Effects, and Criticality Analysis (FMECA), are primarily qualitative methods developed to specifically identify failure modes for a product or process, while also providing an understanding of risk to support corrective action [32]. These techniques are bottom-up approaches that start with identification of all system components and associated failure modes. Effects of the failures on both the component and system are then defined based on tacit knowledge or historical data, with risk prioritization or criticality measures being derived as the final step to support risk mitigation actions. FMEA and FMECA provide comprehensive means for analyzing single elements in a hardware system to understand single-point failures and design requirements, but they rely on available knowledge and do not consider the effects of multiple interacting

failures [33]. These methods also have trouble accounting for operating procedures that allow for human variation and error [34]. Deviations in software and human behavior are difficult to assess, usually not limited to discrete cases, and often are not explicit failures, thus these methods are not well-suited to identify resultant hazards [35]. Overall, FMEA and FMECA can be used in safety analyses if limitations are recognized, but they do not provide a comprehensive approach to hazard assessment in modern, complex socio-technical systems.

FTA is a quantitative method leveraging probabilistic failure assessment to identify the causes of hazards as opposed to hazards themselves [33]. While based on the same linear failure event model as FMEA and FMECA, this method is a top-down, tiered approach to explore foundational failure events contributing to a defined system level hazard. Boolean logic defines the combination of failure events into each higher level of the tree and can be used along with historical or predicted probabilities to quantify probabilities of failure. The value in this technique for hazard analysis is more in the qualitative identification of failure event scenarios and hierarchical relationships rather than quantitative outcomes based on questionable probabilistic attribution [33]. A minimum number of cut sets of the logic-tree can be identified by selecting the basic sets of events required to yield the top-level event. These cut sets allow for a focused examination of causality to support requirements development and focused elimination of single-point events in the system. Drawbacks are similar to those of FMEA and FMECA, in that system hazards resulting from failures only are considered and tacit or historical knowledge of system failure events must be available to identify causality. Fault trees also require a high level of system detail and are not useful for phased system states [33].

Given the basis in linear chain-of event accident modeling and the required level of understanding of system constituents, reliability-based hazard assessments are inherently limited by both the strict assessment of failures and the availability of historical information on constituent elements. The hypothesis presented in this investigation invokes the concept that producibility losses, as with accidents in modern complex systems, can result from interactions of socio-technical elements where no explicit failure may be present. Given the unique nature of development organizations and the products that they generate, methods

are also needed that can identify hazards without the availability of tacit knowledge on where losses are likely to occur. Reliability-based hazard assessment methods are therefore not sufficient to extend to the problem of analyzing producibility governance in aerospace product development environments.

2.6.2 Functional Hazard Assessment

System safety methods in aerospace and substantiation of regulatory compliance are based on industry standards and defined government regulatory means of compliance in guidance material or military standards. A commercial industry safety standard is Aerospace Recommended Practice 4761 (ARP4761) from the International Society of Automotive Engineers (SAE). This standard is reflected in the content of associated military standards for system safety design and validation. While encompassing previously presented reliability-based techniques for system safety validation, ARP4761 also specifies use of a hazard analysis method known as functional hazard assessment (FHA) for early assessment of systems. Similar to reliability-based techniques, the method focuses on the examination of functional failure conditions but starts at the product system level before looking at individual lower-level failure scenarios.

Analogous to the techniques of preliminary hazard assessment and operational hazard assessment, this approach requires an analysis at the product (aircraft) level and a subsequent analysis at the system level for functional failures. Both examinations involve identification of functional states and associated failure conditions to allow for assignment of severity and development of system requirements. Identification of single and multiple failure conditions are first defined at the product system level to allow for assignment of design assurance levels to systems based on severity classifications. Consistent with the allocation of functionality, design assurance levels are then propagated to system levels and functional failure scenarios are assessed at the system level when sufficient maturity in definition is available [36]. While more comprehensive than the previously presented reliability-based approaches, functional hazard assessment and analogous techniques still focus on discrete failure cases and have difficulty addressing system or constituent element interactions. There is limited guidance on understanding causality for specific undesirable states and the assignment of quantitative

severity creates additional difficulty in assessing human, software, and organizational causality [37]. The failure focus and noted limitations do not lend this hazard analysis technique to extension for either a non-physical system and or analysis of potential hazards impacting other emergent system properties such as producibility.

2.6.3 Hazard and Operability Analysis

Hazard and Operability Analysis (HAZOP) was developed in the chemical process industry. It supports expanded analysis of hazard causality through systematic analysis of potential deviations from intended behavior. The fundamental approach for HAZOP analysis is for a team of experts knowledgeable on system processes to sequentially walk through processes, examining each element of the physical system for deviation from intended function, prompted by standard guidewords. Subsequently cause and effect in relation to these deviations is assessed [33]. Conceptual system architecture forms the basis for the analysis.

HAZOP has many attributes that support consideration for an extension to producibility governance. It does not require hazards resulting in a potential loss to be identified before an analysis and it promotes creative thinking while adhering to a systematic assessment process. It allows for identification of complex hazard events resulting from propagating failures. The practical application of the technique also forces cross-functional conversation, which not only provides more prospective on system design, but also can in itself drive better system outcomes for emergent system properties like safety or producibility. Unfortunately, the allowed variation in human judgment inherent to the method and level of expertise required create drawbacks for implementing this technique in assessing complex socio-technical governance [33]. Sufficient perspective is needed beyond the capabilities of most individuals to extend this method to producibility governance. Also, the HAZOP analysis method looks for proximal events driving hazards which also will not reflect the phased nature of development organizational governance [33].

2.6.4 System Theoretic Process Analysis

A recently developed hazard analysis method based on the system theoretic accident model and processes (STAMP) is system theoretic process analysis (STPA). STAMP is a model of accident causation that invokes control theory to examine where interactions between constituent elements of dynamic systems fail to enforce a given set of desired safety constraints [31]. The model goes beyond failure scenarios to encapsulate the effects of system complexity, influencing process models, and adaptations with time thereby allowing for more comprehensive assessment of losses in socio-technical systems [31]. STPA is a tool that leverages the STAMP causality model to identify sources of hazards that can result in violation of behavioral constraints for the purpose of designing or improving system control of an emergent property. STPA can be invoked at any stage of a system life cycle to help understand ways to improve systems and identify expected changes in the system with time [31]. Implementing STPA involves conduct of the following macro-level steps [31]:

1. Identify the potential for inadequate control of the system that could lead to a hazardous state
2. Determine how each potential hazardous control action identified in Step 1 could occur.

Completion of the first step requires identification of hazards and associated system constraints that must not be violated to maintain system safety. With hazards identified, the hierarchical control structure for the system is developed and associated control actions are assessed for either inadequate control or omissions. In the case of a socio-technical system, a supervisory control relationship with controllers based on discipline responsibility is invoked as shown in Figure 2-8.

The second step examines causality for the identified inadequate control actions that could result in the violation of safety constraints. Systematic examination of individual theoretical control elements depicted in Figure 2-8 is conducted at the loop level for potential flawed or missing information, inadequate process models, delays, component failures, disturbances, or changes with time that could explain control insufficiency. Causes that cannot be shown to be impossible must be addressed through assessment of governing system de-

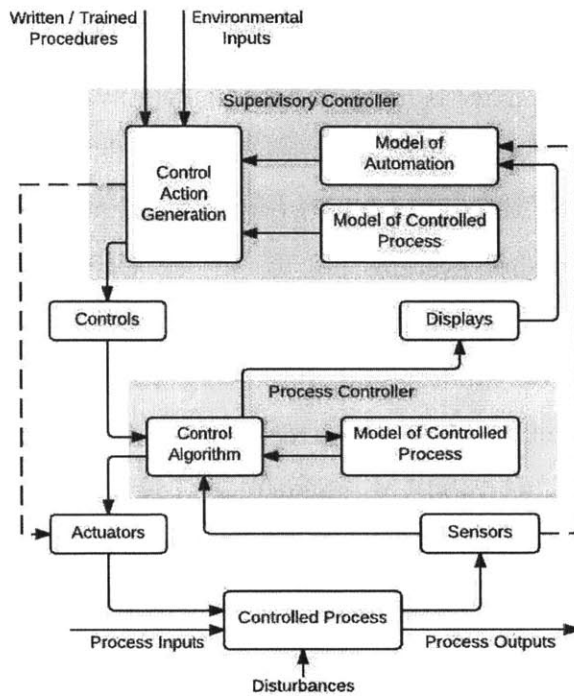


Figure 2-8: Supervisory control structure model used to assess the control hierarchy and interactions in socio-technical process governance [31]

sign with potential changes required if mitigations are not identified [31]. While a detailed examination of STPA is not provided in this overview, the subsequent investigation will walk through the analysis in detail providing the necessary foundations for extension to emergent system properties other than safety. Reference to the work of Leveson [31] is recommended for understanding of application to system safety.

With an ability to examine causes of loss for emergent system properties beyond elemental failures and explicit guidance on how to identify inadequate control for the purpose of designing a better system, STPA is an ideal hazard analysis technique for assessing governance of socio-technical system emergent properties. The subsequent investigation leverages the described STPA process to examine producibility control in an aerospace development organization. The goal is to identify insufficient governance elements that can be addressed through risk management practice. A number of previously invoked extensions are first presented to examine the value in STPA methods beyond system safety and identify alignment opportunities between emergent system properties.

2.6.5 STPA Extensions

While STPA is a hazard analysis technique developed for analysis and design of system safety architectures, the basis in control theory and system engineering lends to the application of methods to non-safety related control and early risk management. Given the recent development of STPA, limited extensions have been presented in literature. This section presents a brief review of know extensions of the technique and then discuss how STPA can be used to develop leading indicators for general risk management.

Security is one emergent property for which an STPA extension has been invoked to improve architectures responsible for the prevention of losses. Young and Leveson examined the use of STPA to improve tactical approaches to cyber security for preventing losses of data integrity and availability. By allowing for the identification of specific security scenarios, STPA supported improved strategy for protection mechanism definition by security specialists and improved methods of communication to decision makers [38].

STPA has also been extended to examine business systems and financial operations. Buck examined corporate ethics through the analogy of moral lapses to accident losses to identify causality of ethical hazards in business. He found that interactions among ethically reliable individuals could still lead to unjustified risk for corporate stakeholders [39]. Spencer used the analogous causal analysis using STAMP (CAST) to understand context and causality behind the collapse and acquisition of the Bear Sterns investment bank in 2008. It was concluded in this investigation that Bear Stearns decision-makers (or controllers) in the organizational system did not understand the extent of influences on market variation and did not have adequate organizational governance to reinforce mitigation of market risk. Likewise, regulators were focused on narrow modes of financial failure and not risks to the entire market system. Recommendations were provided for simplified financial industry oversight that focused on the dynamic interactions of financial firms with the market and with their own governance systems [40].

Abdymomunov examined hybrid socio-technical systems in post-Soviet Eurasian societies to understand how emerging challenges for political systems can be identified and their impacts on safety. It was concluded from this application of STPA methods that insufficient

capital investment and the development of maintenance backlogs in government systems can contribute to failures of public infrastructure [41].

Fleming, while using STPA for traditional safety hazard analysis, presented a notional extension that allows for assessment of operational concepts and requirements maturity in conjunction with safety hazard analysis. The result was a method called Systems-Theoretic Early Concept Analysis (STECA). This technique provides significant value for system engineering in socio-technical systems associated with early product development by allowing for hazards to be addressed and mitigated without product detail or mature development efforts [37].

Probably the most relevant STPA extension for this investigation is that by Goerges in which she found that application of STPA for analyzing sources of quality loss yielded more causal factors than FMEA or FTA, and equivalent to the use of Robust Design Methods. The emergent property of quality was equated with safety, quality losses were treated as accidents, and unsafe control equilibrated with inadequate design and process control. It was also determined that expanded guidewords may be required when extending STPA to quality management system analysis [42].

Common themes from the extensions of STPA were that application of the methods provided a more comprehensive means of dealing with modern system complexity than traditional approaches, and causality in socio-technical systems can more effectively be explored with STPA. These themes are consistent with the goals of STPA development for system safety. Given the demonstrated value in systems of similar complexity and scale to aerospace product development environments, STPA is employed in the subsequent investigation to examine causality of producibility losses and develop improved risk management practices.

2.6.6 STPA and Risk Indication

The focus of this investigation is on identification of leading indicators for producibility risk. Extension of a hazard analysis technique to facilitate risk identification must not only result in the discrimination of risk factors to which the system has vulnerability, but it also must provide for systematic identification and monitoring. STPA has been shown by Leveson to provide this capability by allowing for identification of leading indicators through examina-

tion of assumptions associated with non-mitigated causality of hazards. The basic hypothesis presented by Leveson is that useful leading indicators can be identified based on the assumptions underlying safety engineering practices and on the vulnerability of those assumptions rather than on likelihood of loss events. [43]. Consideration is given for assumptions related to engineering decisions, assumptions associated with management and organizational structure, and assumptions that contribute to coordination risks. Leading indicators are defined based on assumptions associated the design of system controls and actions taken to mitigate system hazards. In conjunction with vulnerability of each assumption and failure severity, monitoring protocols can be defined to specify when and how indicators are monitored, as well as hedging action that should be taken to mitigate associated risk [43]. It was noted in development of this methodology for leading indicator identification that indicators may vary between organizations even in the presence of similar system control structures, hazards, and safety constraints. Beyond the examples for traffic collision and avoidance systems and the Columbia shuttle accident presented by Leveson, chronologically recent specification of the leading indicator approach based on STPA has had limited dissemination into industry risk management approaches. Additional application of the leading indicator derivation methods are needed to explicitly demonstrate the resulting improvement in efficacy of associated risk management. By selection of STPA as the underlying technique for this investigation, it is a hope that the described extension and leading indicator derivations contribute to the validation of STPA for operational risk management.

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Chapter 3

Dynamics of the Model Organization

It is proposed in this investigation that organizational design and phased governance are critical aspects in the management of producibility risk. An understanding of not only the current organizational structure at Aerospace Corporation X, but of its alignment to business and market strategies and inherent dynamics are needed to support an investigation of efficacy for existing risk management. This section provides an overview of the organization, culture, and politics at Aerospace Corporation X with a focus on recent transitions and operating attributes observed during the practicum period. It will conclude with a brief examination of the alignment of the organization with its explicit processes for competitive positioning and an analysis of explicit and implicit incentives that factor into the capture of risk within the organization.

3.1 Structure and Functional Transitions

A basic but important corporate assessment is an examination of organizational structure and its alignment to business strategy and business practice. This section provides a brief overview of the Aerospace Corporation X organization as it relates to the product strategy and development. Specific functional transitions within manufacturing engineering are also discussed due to the relationship to producibility governance and risk management. The section closes with reviews of integrated product team structure and human resource management to support subsequent development process investigation.

3.1.1 General Organization and Business Unit Structure

Aerospace Corporation X has a large, distributed network of Engineering and Operating facilities mostly within the eastern portion of the domestic United States. Total employment exceeds 15,000 people with a large integrated contract workforce. Given the significant proportion of sales to domestic and foreign governments, most facilities are focused on the production and delivery of military products. Current production of commercial products has been consolidated to a separate domestic location that was acquired in an acquisition. Both commercial and military products leverage joint fabrication, sub-assembly, and test and evaluation operations spread among the various Operating sites. All products are supported by a large, distributed supply chain of primarily domestic suppliers due to the requirements of U.S. DoD acquisition programs. Production rates for most product programs are below 100 units per year with the exception of variants for a long duration legacy military program, which has achieved maximum production rates between 100-200 units per year.

The existing market strategy for Aerospace Corporation X is to provide aerospace products that deliver superior performance and capability, while also maintaining a high level of safety and reliability to protect the end user. A focus on product services and solutions has become more relevant in recent years as a result of economic volatility. Cost has traditionally been secondary in the product strategy due to the focus on military acquisitions, but there is some shift in this prioritization given constrained fiscal environments and operating cost focus. The primary strategic focus on performance and capability of products has resulted in an Engineering-centric organization that focuses on long lifecycle weapons systems for the domestic military from which derivative products are developed to serve foreign militaries and commercial markets. Production Operations also plays a central role in the organization, particularly in wartime periods, to facilitate on-time delivery of mature product units to satisfy customer operational demand. Business and supply chain management operations are smaller constituents within the organization, having department sizes varying based on the operating site and product market.

Aerospace Corporation X has undergone a number of transitions in organizational structure within the last two years. While specific, lower-level functional transitions will be sub-

sequently assessed, a review of business unit structure is needed to understand governance stemming from product and functional alignment. Aerospace Corporation X previously had a market-based top-level structure, with supporting functions having internal matrix organizations. Recent reorganization driven by fiscal constraints impacting government customers has resulted in a hybrid of a market and matrix-based organization at the top-level. Up until recently, the company operated with three independent subsidiary companies serving the commercial, military, and aerospace services markets as shown in Figure 3-1. Within this structure, there was alignment of supporting business operations to each company with overlap in Engineering teams and production operations between the commercial and military companies. This prior structure benefited from centralized knowledge management within Engineering and Operations, but there was redundancy in business operations between the product focused companies.

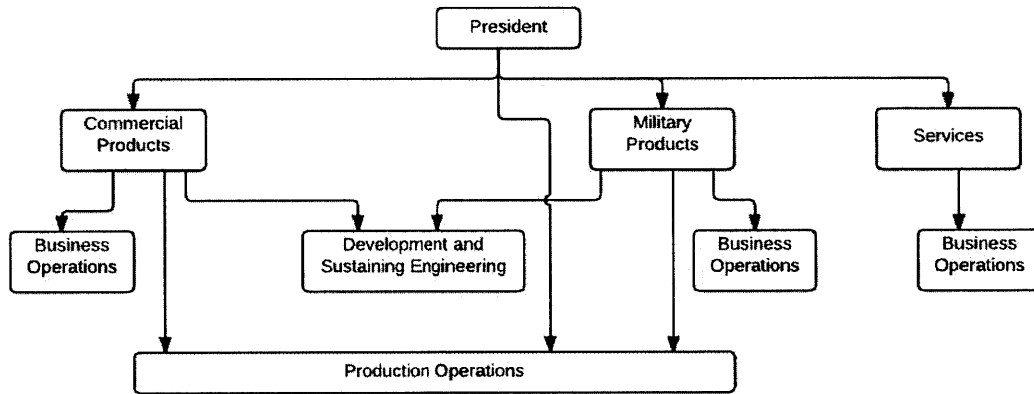


Figure 3-1: Aerospace Corporation X market-based structure prior to recent transition

In the current structure, the market-based aspects of the organization are focused on the lifecycle of products with only two segments, a commercial products and services business and a military products and services business. This organization holds the potential to maintain stronger customer relationships throughout the respective product lifecycles. These primary market-based units are juxtaposed in the top-level organizational structure with business operations, engineering, and development program management as shown in Figure 3-2. While supporting efficiency through centralized business and engineering operations, this merger of a market-based and matrix organization results in conflicting oversight particularly

for product development efforts. There is also a conflict with development program phasing in the interface with production operations. These conflicts are not insignificant and will be examined as part of exploration of the hypothesis of organizational influence on producibility governance.

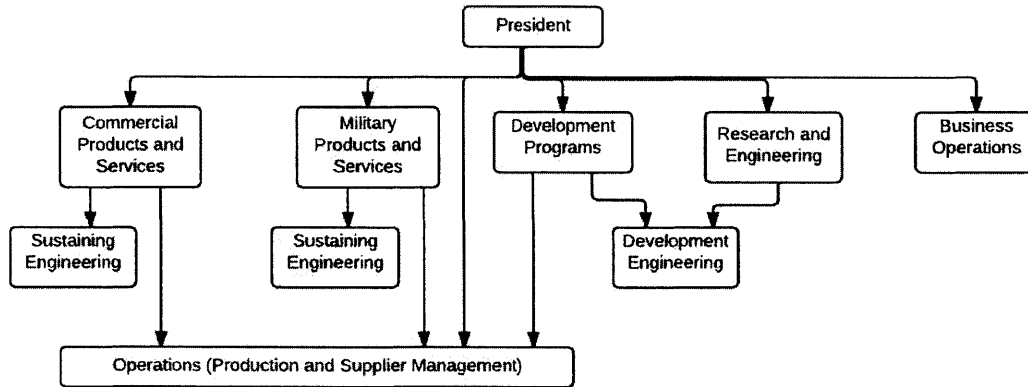


Figure 3-2: Aerospace Corporation X market-based structure after reorganization

Examination of the Executive reporting structure related to the current organizational structure further highlights the number of product and functional based divisions within the company. Figure 3-3 provides depicts the first tier of management below the President.

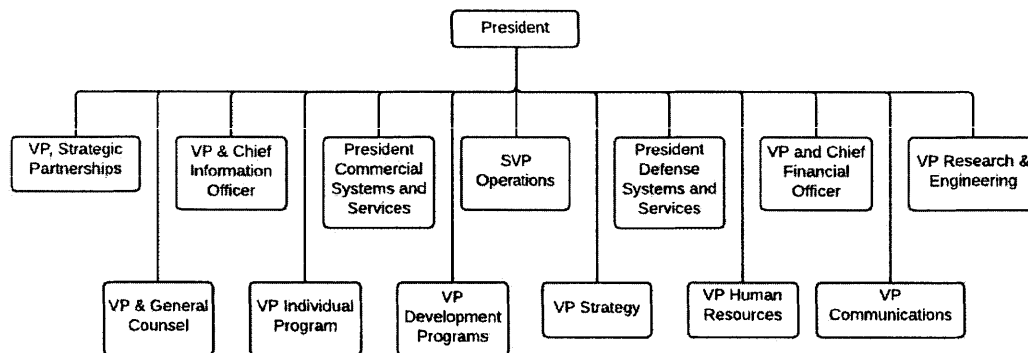


Figure 3-3: President and vice-president level management structure

Given the focus on Engineering and Production Operations at Aerospace Corporation X, each of these business segments has an expansive sub-tier organization with a traditional matrix structure. The Engineering organization has design-focused Engineering IPTs supporting the various development programs that span the various functional disciplines as

shown in Figure 3-4. In addition there is a manufacturing and tooling engineering discipline that supports all the programs through its own internal matrix organization. All of these groupings also have reporting relationships to Development Program Management. As is typical with large matrix organizations, there is a benefit to retaining functional expertise within Engineering disciplines but the complicated structure tends to induce complexity in information flows and supporting standard work processes.

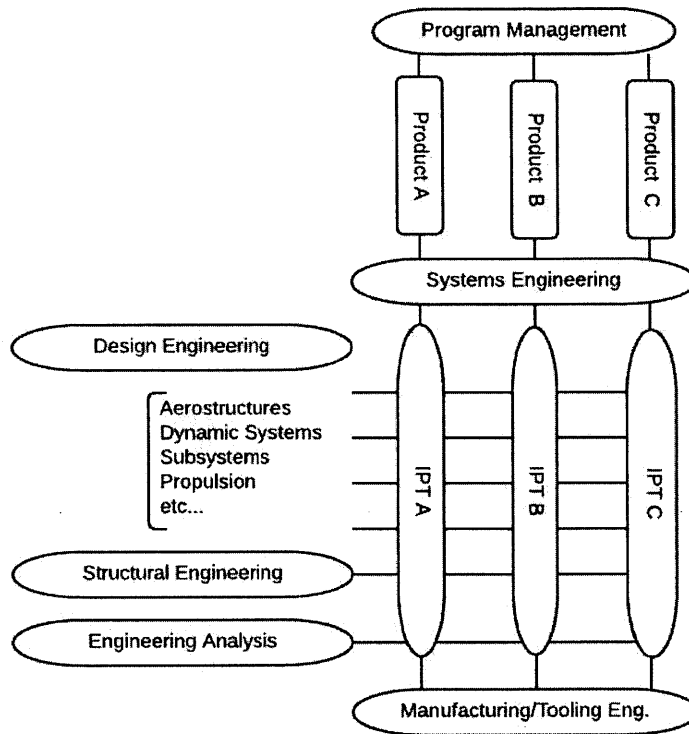


Figure 3-4: Engineering organization matrix structure

Similarly, Operations has functional disciplines that support the various product programs as shown in Figure 3-5. While reporting to Program Management is not a primary factor in Operations, there are still barriers to linking across the functional disciplines, particularly between Supplier Management and Quality. In addition, given the impact of this segment on operating expense (or product recurring cost), there is significant pressure on available resources which must be mitigated by allocation of labor and assets between the Operations functions. These constraints limit information flows and standard process familiarity, thereby challenging producibility governance.

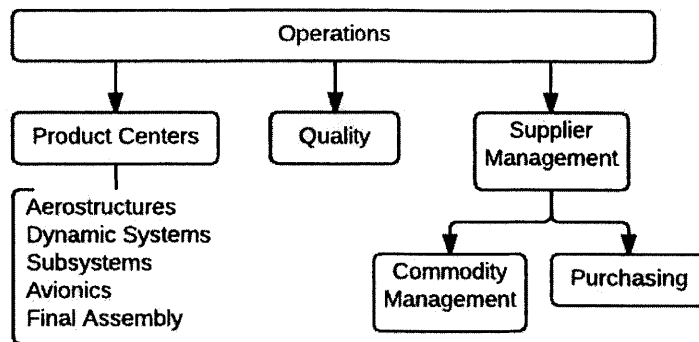


Figure 3-5: Operations Organizational Structure

3.1.2 Corporate Oversight

Given the motivation for this investigation is partially rooted in corporate supply chain strategy, it is important to understand the relationship of Aerospace Corporation X to its parent corporate holding company. Aerospace Corporation X is one of several aerospace product and services businesses under the parent company, although it is the only company that produces complete weapons systems and air vehicles. The other aerospace business units are more focused on the commercial and international aerospace markets, with less than 25% of sales to the domestic military market. This reflects the overall percentage of parent corporation sales to the domestic military market, which has fallen to less than 20% of sales across all subsidiary businesses. The other grouping of companies under the parent holding company are focused on construction and industrial products. Gross margin in these companies tends to be higher but sales are more cyclical due to the influence of the domestic and international construction markets.

The aggregation of subsidiary companies into two distinct product groupings does not have bearing on producibility governance within Aerospace Corporation X, but the differences between the aerospace business are pertinent. Aerospace Corporation X is the only subsidiary company with a majority of sales to military markets, and therefore is subject to differences in working capital for development and operations. Military aerospace development cycles, particularly for the domestic market, involve high levels of customer oversight, incremental funding based on milestone payments, and more extensive validation and veri-

fication requirements. Subsequent low rate production contracts, while subject to some uncertainty, are often well defined allowing for leveling of future production demand. Coupled with contract structures that have traditionally compensated for cost overruns, development programs tend to be protracted and regimented with more focus on product performance and less focus on time to market. Commercial aerospace development is driven by competitive innovation and constraints for operators, therefore it is more sensitive to time-to-market considerations and production rate. Long run demand forecasts tend to have more uncertainty so step changes in rate are defined for near-term production after product verification and certification. Commercial development, while often still protracted, is funded primarily by internal research and development funding so there is an ability to allocate resources with more flexibility based on management discretion. Given the time-to-market and rate change considerations, elimination of producibility risk implicitly holds more value. The difference in management valuation of producibility risk within individual companies and organizations cannot be quantified, but the differences in program management focus and operational strategy must be considered when assessing the level and extent of producibility governance.

3.1.3 Manufacturing Engineering

An important organizational transition that needs treatment for its relation to producibility risk within Aerospace Corporation X product development is the alignment of the manufacturing engineering discipline within Engineering and Operations. Manufacturing Engineering is responsible for production process planning and the use of manufacturing technology to produce a product according to its configuration definition and operating constraints. Given the association with physical production, manufacturing engineering is traditionally integrated later in the aerospace product development cycle when there is sufficient configuration to develop the details of process planning. The majority of the disciplines statement of work is defined for the production engineering and test phase of the program. Given the relationship to the physical manifestation of the product, manufacturing engineering has both significant oversight and influence on producibility. As will be discussed during an examination of producibility governance, manufacturing engineering expertise is demanded

earlier in aerospace product development as the level of product complexity increases. This is a result of the need to align and accommodate manufacturing constraints within the integration of product components and segments, as well as identify insufficient manufacturing technology with adequate lead time for capital allocation and infrastructure improvement.

The manufacturing engineering function at Aerospace Corporation X within the past two decades has existed with various degrees of independence from other engineering disciplines and Operations. Associated with varying independence, reporting and oversight in product development has transitioned within Operations and Engineering. Up until the late 1990s, manufacturing engineering had director level management and operated as an independent functional team, reporting directly to executive management within the Operations organization rather than Engineering. Work statement was focused on supporting production operations, but the organization also served as an external oversight authority within the product development process. In the late 1990s, manufacturing engineering was transitioned in reporting structure into the Research and Engineering organization. Initially, the function maintained a director who reported directly to Engineering executive management. After the turn of the century, the director position was dissolved and manufacturing engineering as a function moved lower in the reporting structure consistent with more specialized engineering functions. Eventually, the manufacturing engineering team members were integrated into the design engineering function. While still maintaining oversight of production process planning, the role was narrowed in terms of development and management oversight. Involvement in most instances of integrated product team development was initiated during release of detailed product definition with continuation to support the transition to build. While this arrangement provided for a more integrated Engineering team with less siloed expertise and more delineation in work statement phasing, independent skill development and integration with Operations was reduced. The transition also came with a reduction in the ratio of dedicated manufacturing engineers in relation to design engineers. As a result of resource constraints and development phasing, work statements narrowed in scope to focus on process planning only.

Around 2012, the decision was made to again breakout manufacturing engineering within Engineering as a separate functional team. Eventually, director oversight was re-instituted

with direct reporting to Engineering executive management. Given the organization transitioned from design engineering teams aligned to segments of the air vehicle, the organization now has individual teams that focus on different aircraft segments. These teams are partially collocated and have varying degrees of structured interfaces with their former design engineering parent teams. The organization maintains oversight of both detailed design releases and production processes, but recruiting and skill management has been difficult due to prior absorption into the design engineering teams. The majority of Engineering interfacing is provided by senior members of the team who were present under the Operations-reporting period. From observations of development team integration, it is apparent that the sequence of transitions has resulted in a lack of familiarity with the role of the function by program management and other engineering teams. Coupled with skill recruitment challenges and dispersion from the integrated product teams, the level of authority is not consistent with past operational alignment and working relationships are not consistent with the period of design team integration. Given their role in producibility risk identification, this segregation is significant and compensation is needed within product development governance. Subsequent analysis will also focus on this dynamic within the product development organization to understand how it influences producibility risk management.

3.1.4 Integrated Product Teams

The commonly used term of integrated product teams is applied within Aerospace Corporation X to development teams responsible for definition and configuration of aerospace products. In the literal sense, integrated product teams are supposed to contain representation of all disciplines necessary to realize a product consistent with organizational strategy and requirements. The benefit of the cross-functional representation is that barriers to communication and information transfer are low, enabling internal decision-making and comprehensive assessment of problems. At its most fundamental form, integrated product teams in product development organizations evoke lean production principles of responsiveness to change, pushing decision-making to the working level, and minimize buffering of in-process information.

Aerospace Corporation X primarily applies the concept of integrated product teams

within its Research and Engineering functional organization. Integrated product teams are used to support product development efforts by combining varied engineering disciplines under the leadership of design engineering management. These teams support product segment development and configuration change by reporting to program managers and interfacing with operations and product evaluation and test teams. The previously presented Figure 3-4 depicts the relationship of these teams to the organization.

While leveraging the capability of several engineering disciplines, these teams are limited in scope. These integrated product teams do not contain team members from System Engineering and Manufacturing Engineering. Working interfaces are closely established through process with System Engineering due to the role of this function in product development oversight and risk management, but Manufacturing Engineering interfaces are less defined with the exception of the configuration release process. Beyond integration with Engineering disciplines, Aerospace Corporation X integrated product teams do not typically reflect roles within Operations, notably Quality and Supplier Management. Incorporation of production process capability is left up to Manufacturing Engineering expertise and supplier interfaces occur through data transmittal and direct conversations with supplier Engineering organizations if required. This separation is good in that it prevents the integrated product teams from absorbing statement of work beyond their capability and affords management gated opportunities to assess the development process, but it also results in a lack of understanding of external disciplines and available information to support product definition. This isolation as it relates to producibility governance is significant and will be elucidated through subsequent analyses.

3.1.5 Staffing and Recruitment

A final aspect of organizational design that is pertinent to producibility risk management is the approach of Aerospace Corporation X to staffing and resource recruitment. All organizations within Aerospace Corporation X maintain oversight of direct and indirect labor in terms of full-time equivalent heads. They are supported by the Finance organization in reviewing labor charges vs. headcount, as well as overtime and limited measures of productivity. Additionally, on development programs, DoD Acquisitions dictate the use of the

Earned Value Management System (EVMS) principles to assess schedule and work statement execution, in conjunction with cost. While a more detailed discussion of EVMS will be presented when reviewing the product development case study, it is important to note this detailed oversight to convey the internal focus on management of staffing levels. This focus is important given the domestic military product strategy for Aerospace Corporation X and the oversight of the U.S. government on overhead burden rates for defense contractors.

While significant focus is invested to maintain balanced staffing levels, organizations within Aerospace Corporation X vary in their approach to recruitment of additional staffing to support product development efforts. Engineering has the most robust approach to recruitment with an information technology system for projecting staffing needs by skill along with associated confidence intervals. During the proposal phase of a product development effort, staffing projections are generated based on the projected statement of work within individual Engineering disciplines. Program management then tailors these staffing levels when program budgets are available and management reserve funding has been withheld. While this tailoring can be misguided by a disconnect in understanding of the work statement, the system does support comprehensive forecasts that can be transmitted to Human Resources to facilitate advanced program staffing.

Within production and business operations disciplines, the approach to recruitment and staffing projections is less clear. Some disciplines such as Sales and Marketing and the proposal group maintain staffing that transitions between new program work statements as required. While this approach is adequate in these disciplines, their program involvement has a well-defined statement of work and is relatively succinct in comparison to the development cycle. For most other operating disciplines that support a development effort, there is early assignment of program responsibility to management and some statement of work definition to support the proposal, but limited forecasting of resource and skill needs. Supplier Management and Quality were two areas where forecasts for future staffing to support development efforts were not well defined. This often places the product programs in a reactive staffing effort when their portion of the work statement materializes. In addition, it generates erratic demands on the human resource organization to accommodate near term resource requests. Coupled with a recent reliance on contract staffing, it also creates a challenging environment

for targeted skill recruitment and long-term knowledge management.

The organization could benefit from a more robust and uniform forecasting system for staffing across the disciplines. Not only would this level the demand on human resources, but it would allow for strategic resource planning where buffers or early staffing could be implemented for critical skills. Constraints imposed by maturation of the organization between product development phases will be examined, along with the role of human resources in the producibility governance structure.

3.2 Culture and Externalities

An important supporting aspect for governance in a large socio-technical system is the culture and beliefs of the supporting employee base. This section examines key aspects of culture at Aerospace Corporation X as they relate to aspects of producibility. Treatment of select external drivers of culture are also presented to understand constraints to potential changes in organizational structure and risk management.

3.2.1 Product and Customer Focus

Management and employees at Aerospace Corporation X are committed to the performance of their products and serving the end user. Given the legacy as a domestic military supplier, there is a strong supporting sentiment for the military and concern with the ability to serve warfighters. This sentiment is not only reflected in general attitudes and frequent conversation about the military, but the mission statement which roughly translates to we always bring passengers home safely. The pervasive sentiment drives people to focus on pursuing the highest levels of performance and safety, which is a necessary attribute for an aerospace manufacturer. This focus also drives an Engineering design and product-centric organization, with processes supporting extensive development, validation, inspection, and customer oversight. The result is less focus on program-level market timing, even with significant team-level schedule focus. There is also less focus on cost constraints, which counters some of the challenges being faced in the military and defense markets by Aerospace Corporation X. While safety and performance are paramount to marketability of current

products, a more pervasive competitive focus would benefit the organization by aligning working level teams with current externalities and operating efficiencies. This focus could be instituted by addressing complexity in procedural governance that impacts producibility, as well as balancing focus on performance and schedule with cost and quality.

3.2.2 Military Influence and Hierarchy

In addition to the strong support of military customers, Aerospace Corporation X also employs many domestic military veterans. This reinforces internal customer focus and provides a strong leadership presence within the organization. Many of the recent veterans have been successful within the organization and ascended rapidly into higher levels of management. Unfortunately, some negative sentiment was observed towards the rapidly ascending veterans due to the view that they did not earn their stripes within the working level teams. Beyond this sentiment, the ascension in conjunction with the customer cultural focus reinforces a strong and respected hierarchy within the organization. Tactical solutions to development and operational changes are directed by senior and executive management, with lower level supervisors focused on execution of the baseline work statement within their teams. This creates challenges at the director level, the lowest level of executive management with oversight of individual functions, as there is an expectation to both answer for execution and implement strategic vision. The near term commitments associated with execution demand most of the attention of directors, thereby limiting their bandwidth for implementing strategic change. The overall execution focus reinforces growth in procedural complexity and governance, as resolution to most problems was observed to occur through institution of additional process gates or executive oversight. There is opportunity to both improve operational efficiency and facilitate increased producibility by reducing procedural complexity. Allowing for problem resolution within the working level teams that have a demonstrated understanding of the product and process will also support these improvements.

3.2.3 Management of Complexity Through Relationships

The complexity of new aerospace product development and long product life-cycles promote stable working level teams over long durations. This environment contributes to strong internal relationships between team members that are carried forward to facilitate future product development efforts. It was observed during the practicum period that relationships are the primary means of executing work statement within and especially across Engineering and Operational team boundaries. This is not only driven by the tenure of employees within the organization, but also procedural complexity and misalignment. Standard work does not reflect practice particularly in non-design and Operation teams working on product development efforts. Unfortunately, the relationships and the mis-aligned standard work create barriers for entry for new team members. A significant integration period was noted for less experienced team members who either came from external groups or organizations. Focus on onboarding to facilitate understanding of internal processes coupled with repeated cross-functional engagement between teams would lessen the dependence on relationships while still respecting the existing working level team culture.

3.2.4 Demographics

With respect to knowledge retention and managing the current system of procedural governance for product development, the expertise within senior Engineering staff members and non-executive management supports continued execution with the growth in product complexity. As is consistent within the aerospace industry, there is a "double-hump" phenomenon in the age demographic of the Engineering workforce. Specifically, there is a headcount gap between a large percentage of the workforce nearing retirement along with a large less experienced population. The effect of this demographic profile is that a lower percentage of the Engineering workforce falls within the 10-20 year experience range during which advanced knowledge transfers to the less-experienced team members. This is pertinent to producibility and risk management given that standard work and processes must balance this gap in tribal knowledge within the teams. As discussed in the organizational analysis, procedural misalignment with working practices prevents the necessary feedback for not only improve-

ment, but also risk identification. While standard work adherence cannot be guaranteed, organizational knowledge needs to be captured to facilitate onboarding and team alignment.

3.3 Functional Politics

Power and associated political viewpoints within an organization influence adherence to standard policies and procedures. These attributes of the organization can encourage or limit proactive risk management within teams. This section presents select observations of power and attitudes within Aerospace Corporation X functional teams responsible for producibility risk management.

3.3.1 Engineering Discipline Oversight

It has been asserted previously that the product focus at Aerospace Corporation X contributes to an Engineering-centric organization. This Engineering focus affords the product development engineering IPTs power within the organization. Specifically, design engineering as a discipline is provided a significant amount of power by IPT management; whose members typically ascend from this discipline. This power maintains product focus and affords the opportunity to resolve product performance and quality issues through configuration change. It also supports significant resource allocation to design phases of the program when producibility risk can be mitigated. The unfortunate aspect is this power also constrains perspective within the Engineering IPTs, as well as Program Management who relies on IPT leaders for assessment of configuration risk. The design engineering perspective drives significant focus on meeting configuration and performance requirements within Engineering and Program Management schedules. While loosely connected to Operations through production need-date scheduling, opportunities for communication of operational concerns and manufacturing constraints are minimized due to the perspective of the design discipline. As previously noted, relationships can be leveraged in this environment to address producibility early in a program but established processes support reactive resolution to quality challenges during the build. While the limited observations do not dictate a forced re-balancing of power, cognizant design engineering management does need to leverage their

power within the broader organization to ensure cross-functional perspective on operational constraints and integrated risk management.

3.3.2 Operations vs. Engineering

Operations and Engineering have to work together to not only mitigate early producibility risk, but ensure producibility levels are maintained through efficient quality monitoring and value engineering efforts. The power afforded to design engineering IPTs allows for isolation from Operations during the initial build and at-rate production. While processes support feedback on manufacturability and quality issues for sustaining engineering team resolution, Operations teams are ultimately responsible for maintaining quality and problem resolution within the current governance structure. Balance of sustaining responsibility is needed to encourage proactive engineering engagement with continued operations at the team level. The resulting engagement will not only facilitate learning, but also earlier engagement on operational risk management than exists in current product development processes.

3.3.3 Represented Labor

The hourly production workforce at the primary commercial and military product manufacturing sites for Aerospace Corporation X are represented by unions. This represented labor format is typical of most domestic companies within the aerospace industry with the specific unions varying by geographical location. The primary contemporary purpose of the union is collective bargaining, but it has a significant role in day-to-day resource allocation, employee retention, and performance oversight. The union operates under a seniority-based system, with promotions and associated wage increases directly tied to the duration of an individual's internal production experience. The benefit of this system is that it contributes to retention of skilled employees and also prevents wage compression between senior team members and new employees. In addition, job descriptions for skilled tasks can be tied to the seniority system allowing for assignment of highly-skilled operators to complex fabrication and assembly tasks. This promotes more rapid reduction in recurring cost with new product production, or moving down the learning curve, due to carryover of skill from one program

to the next. While there are tangible benefits in skill, there are also significant cultural challenges associated with the union presence.

One significant drawback that contributes to political strife is that a performance management and development system is not established under the collective bargaining agreement. Beyond blatant violation of the code of conduct or participation in activities illegal under statutory law, the ability of management to work directly with employees on improved individual performance and development is limited to oversight of job completion and attendance. Initial job training is provided to all production employees and there are opportunities for self-directed continued development, but the system is not robust for management of workplace performance. Represented employees are managed by hourly supervisors, or shop leads, who interface with management. If represented employees are not meeting the performance or quality expectations of the organization, management works with shop supervisors to resolve the problem. While shop supervisors are usually high performing members of the team, they are represented by the union and thus have incentive to minimize internal team politics. The result is that employees are provided guidance on their performance but do not have specific avenues for performance feedback or development. Unfortunately, the only leverage that remains for correcting performance of an otherwise present and contributing team member is to work with the union on re-assignment to another position. This process can be tedious and most managers are incentivized to avoid this action, in addition to direct employee engagement, due to abuse of grievance filings within the workforce.

The more significant impact of current union relations is the resulting attitudes and cross-functional barriers that are generated and reinforced within the three prevalent categories of the workforce: operations management, salaried employees, and hourly represented employees. It was observed that management tends to feel constrained to work with the union on quality improvement and manufacturing innovation because there is push back from union leadership about the impact to labor positions and overtime opportunities. Salaried employees, particularly in Engineering and core operations functions, do not readily involve skilled operators and technicians in early stage development to incorporate production experience into product design, a direct method of lowering producibility risk. Hourly represented employees experience direct engagement from management and salaried employees only in

response to negative behavior or bulk workforce reductions, thereby assuming that any engagement is associated with a potential detrimental outcome. This prevents dialogue and generation of broader perspective on how a focus on quality, productivity, and innovation can facilitate long term returns to the business and employees.

As with all of the political assessments, there are singularities where these barriers are overcome but in general, there is much to be gained for producibility risk reduction by working with union leadership to adopt a performance management approach. This most likely would be originated through performance incentive and individual development systems for represented employees, but structured avenues of cross-functional engagement also need to be instituted to avoid producibility governance gaps that will be highlighted through the subsequent analysis.

3.3.4 Customer Oversight

With the predominance of product sales going to military customers, particularly domestic military customers, there is significant integration between the customer and product development teams even prior to contract agreement. This interaction continues through the product lifecycle, and in the case of the U.S. government, there is on-site monitoring of production quality and delivery through an oversight organization. This level of interaction is beneficial for product development in that it allows early recognition of requirements changes and collaborative risk management. Unfortunately, given the customer and seller contractual relationship, it also incentivizes delayed problem identification until all information has been assessed by internal or oversight teams. This need for information coupled with the tightly-knit relationship also results in defaulting to additional inspection when product development or production problems encountered. Consistent with Lean manufacturing tenets, more effort needs to be placed on making problems visible when encountered and propagating risk management efforts already in place to avoid increasing reactive inspection approaches. In addition, problem identification needs to be encouraged by both parties without associated blame to prevent unforeseen producibility losses.

3.4 Continuous Improvement Approach

Aerospace Corporation X and its parent holding company both employ a system to drive engagement and competitive focus. This system have been recognized in industry beyond aerospace manufacturing and serve as a framework for analyzing producibility governance. A brief treatment of the organizational system and associated standard work are presented to facilitate understanding of governance during the subsequent analysis.

3.4.1 Competitive Positioning System

At the parent corporation level, a framework is employed that drives focus across all subsidiary businesses and integral functions on the fundamental tenets of lean operations: continuous improvement, elimination of waste, and visibility of problems. This competitive positioning system is credited with allowing the aggregate businesses under the parent organization to achieve annual operating margins above 15%, year-over-year since the early 1990s, up from 5% or lower in prior periods. The system provides tools, methods, and training to support decision making and problem solving. The goal is to support achievement of consistent quality in work products while supporting business strategy and delivery of value to customers. It is a system that both management and individual contributors can apply within the organization and at external interfaces to the supply chain and customers. At Aerospace Corporation X, the system is integrated into both Production Operations and Business Operations, and to varying degrees in Engineering departments. The methods are aligned with previously described ISO 9001 quality standards and focuses on nonconformance management as a means to drive continuous improvement. Figure 3-6 provides a high level overview of how aspects of the system drive improvement. Operating processes that support value-added activities are captured as standard work with included inspection elements. These inspection aspects then integrate with the quality system to allow for capture of three levels of nonconformance to standards or specification requirements: turnbacks, discrepancies, and escapes. Turnbacks are internal to department and allow for problem visibility and resolution before work products are passed along to downstream customers. Discrepancies are nonconformances that require review by parties outside of the related department and

disposition, but will be addressed before impacting external suppliers or customers. Escapes capture the most undesirable form of a quality problem identification where a nonconformance is passed on to a customer or supplier, resulting in significant mitigation action and oversight. There are variations of turnbacks and discrepancies depending on the functional area, but the three categories apply across the organization. Continuous improvement is supported by making nonconformances visible and measuring associated statistics on sources and resolution, as well as by collecting customer feedback through internal and external market feedback assessments.



Figure 3-6: Competitive positioning system employed in Aerospace Corporation X and its parent corporation to support continuous improvement

The extent of implementation of processes associated with the parent company competitive positioning system vary at Aerospace Corporation X by discipline and particularly by phase of a product development program. For internal production operations of mature products, inclusive of quality and supplier operations, the system is robust. It provides an operating rhythm of inspection for hardware and to some extent software, supports statistical measurement, and provides feedback to responsible parties. In business operations, the focus is on information flow in support of current products. Discrepancies and escapes are used less but turnbacks are captured within departments to prevent the flow of errors or incompletions downstream. In Engineering, the competitive positioning system methods are captured through configuration management processes for initiation and release of changes

to either existing released product configuration information or verification information used for quality and regulatory oversight.

For all departments, the use of the competitive positioning system is less apparent in product development processes. Starting in concept development, information and configuration are revised iteratively based on requirements evolution and maturity. At individual Engineering discipline levels, limited groups maintain information on requirements maturity with more focus on controlled incremental releases in requirements through Systems Engineering for configuration control. For contract proposal development, product requirements and work statement estimates are iterated with Engineering, the supply base, and usually the customer until a marketable solution is obtained. As product development progresses, configuration is managed through a change release process with management oversight and control of iterations, but information about drivers of iteration and downstream customer feedback are not captured. Requirements and configuration definition flow to internal production disciplines and suppliers with iteration tracking, but quality measures and impacts to information users are not considered. As the product progresses towards the final definition of configuration and production engineering, nonconformance management is implemented within the supply base but flexibility is provided in accountability to help meet schedule constraints. Once internal fabrication and assembly begins, product nonconformances are managed with oversight through the quality organization per system processes, but the resulting information and change required for mitigation continue to be captured through metrics focused on schedule and iteration count. Opportunity for learning and feedback become more restricted as cost and schedule are negatively impacted.

Ultimately, most of the focus is placed on short term corrective actions to yield improved quality, with bypassing of the quality clinic step in Figure 3-5 where learning and process improvement are nucleated. This not only reduces learning at the time of problem recognition, but negatively impacts long term improvement and cross-functional communication. Changes needed to simultaneously address recurring cost, schedule, quality, and performance are often postponed. It is recognized that the process is constrained by the commitments made to customers and time-to-market considerations, but consideration is needed in the overall business strategy to accommodate the learning and feedback required for long term

producibility gains. The resulting lack of process feedback and temporally constrained mental models can be observed in temporal phasing of producibility governance. This is evident in the included analysis with related opportunities identified to install risk management indicators.

3.4.2 Standard Work

It has been discussed that standard work forms the basis of both the Aerospace Corporation competitive positioning system and producibility governance. It has also been noted that competitive positioning processes are not robust for product development efforts. One of the sources of challenged product development is the consistency in standard work alignment with governance practice in Aerospace Corporation X. Coupled with evolving demands of product innovation, standard work mis-alignment impacts producibility by requiring reconciliation of actual work statement with existing processes during execution. It also prevents a common reference for cross-functional conversation and onboarding of new individual contributors. From a review of the hierarchy and interfaces for standard work across departments shown in Figure 3-7, it becomes apparent that challenges with standard work consistency across departments contribute to inadequate governance.

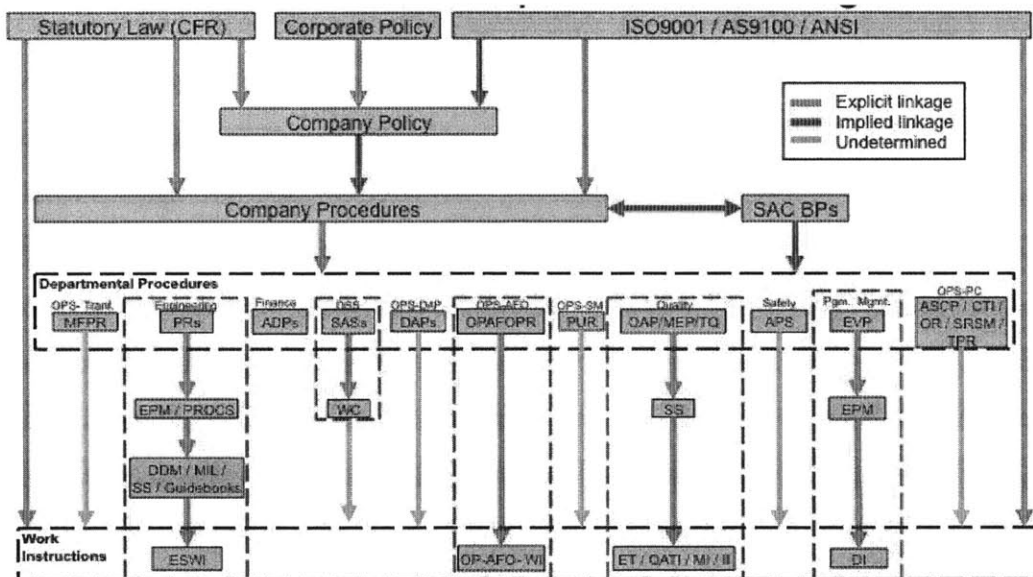


Figure 3-7: Standard work hierarchy within Aerospace Corporation X

The competitive positioning system specifically outlines the value of standard work by iterating a description of standard work as the method by which work is simplified and structured to ensure maximum quality, productivity, and repeat-ability over time”. While robust in its conveyance of value in standard work and approaches to development, the competitive positioning system stops short of defining explicit governance hierarchy and linkages to allow for tailoring to individual company requirements. Unfortunately, this is exactly where the challenges depicted in Figure 3-7 originate. Additional focus is needed on clear linkage and requirements between department standard work. This will support standardized communication, ensure necessary feedback paths are in place, and align processes with operational needs fundamental to maintaining and improvement producibility.

3.5 Explicit and Implicit Performance Incentives

The effectiveness of organizational structure and culture must be maintained through the evolution of the organization. An organization is an independent entity but structure and culture connect its constituent workforce to the strategy and mission. Alignment within the workforce to the structure and culture is achieved through incentivized behavior. Incentives include both explicit monetary or performance incentives, but also and potentially more important, implicit cultural incentives. A brief treatment is provided on observed incentives within the performance management system, change management processes, and quality system of Aerospace Corporation X to support considerations for implementation of proposed risk management methods.

3.5.1 Performance Management

Aerospace Corporation X has a standardized performance management system that applies to all employees below the company president and not represented by the hourly production union. This system governs yearly performance assessment, salary adjustments, and promotions. For represented employees, a seniority-based system is in place that also considers basic aptitude levels for promotion based on written testing. The non-represented system is the focus for this discussion and consists of goal setting activities, managerial and

self-assessment, feedback, salary adjustment, and promotion management. Human resources oversees the performance management process through centralized education of management and departmental human resource generalists. The basic flow for the process in practice is shown in Figure 3-8 and applies to a rough annual cycle, although some variation in duration was observed based on the economic cycle of the business.

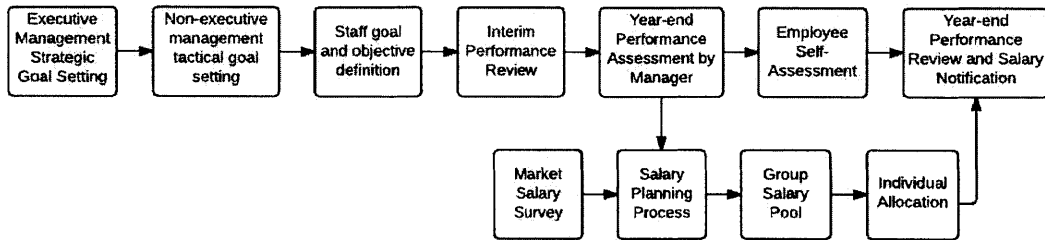


Figure 3-8: Performance review and salary planning process for non-represented labor at Aerospace Corporation X

Strategic objectives flow down from executive management as goals to each function within the organization and are tailored at each lower level for tactical implementation. Staff goals are balanced against specific objectives that are used for performance assessment. Managers are also expected to have objectives of varying degrees of resolution based on their level of oversight. With goals and objectives defined, the next step in the process is interim reviews. These reviews are recommended by human resources and executed at management discretion or employee request. At the end of the annual performance assessment period, the respective manager of the employee completes a performance assessment that feeds the salary planning process. Within the salary process, an employee's assessment is compared against market standards for the employee's job function and level. In conjunction with comparisons to peers in the same team, these assessments are used to define an aggregated salary adjustment pool. From this pool, the respective manager can adjust individual salaries within a limited percentage window per his or her discretion. In conjunction with this salary planning process, the employee is expected to complete a self-assessment of performance. When all steps are complete, the respective manager and employee meet to discuss performance and the results of the salary planning process.

The performance and salary adjustment process provides flexibility to accommodate departmental needs but this flexibility was observed to drive some negative incentives. The

first has to do with interim performance assessments. Depending on the work statement demands within a given team or the managers discretion, employees noted that these interim reviews may or may not occur. If the review does not occur, an opportunity has been missed to ensure employee alignment to goals and team objectives, as well as an opportunity for feedback on ineffective operations and processes. This lack of robust interim review implementation creates some cynicism in the employees with regards to their ability to highlight organizational inefficiency. This can be critical during product development when there is continuous change within both work statement and organizational governance with time, and feedback is needed to ensure adequate producibility control measures are in place. A second and significant negative incentive arises from the integration with the salary planning process and final performance review. The assessment by the respective employees manager supports the salary planning process to allow time for salary pool and adjustment calculations. Unfortunately, the employee self-assessment and end of the year performance discussion with the manager occur after salary planning has been completed. Employees are aware of this sequence and feel that they have little influence over their year-end review. As a result, a significant level of skepticism is held about the process and some employees stated that they did not make a concerted effort to support the process. This again signifies another lost opportunity for feedback, something that can be critical during early stages of product development when producibility is anchored within product planning and definition.

Beyond the standard performance management process and salary adjustments, incentives awards and promotion consideration vary based on discipline and management vs. non-management position. The following subsections focus on the incentive and promotion practices for executive management, product program management, and staff members to provide an understanding of prospective in each of these producibility influencing functions.

General Management and Senior Staff

While general management does follow described performance management process, they and senior staff members at a level five or higher, have the opportunity for an additional incentive payment. This incentive is based on company performance, individual performance, and employee level. Each level has a defined target percentage of their salary which is then

modified with multipliers for business performance and individual performance. The defined target for the lowest level of management or senior employee is roughly double the average salary adjustment pool for employees not receiving an explicit incentive. The bonus amount can grow depending on their level and individual performance. There are no aspects of the incentive related to specific product program or departmental performance.

Promotions into general management are the result of a combination of seniority and individual performance, with emphasis on the former. Promotions within management, especially at higher levels of the hierarchy, are typically the result of selection by higher-level managers. Some managers achieve promotions through transfers into other departments but most managers do no transition between the three primary functional areas of the organization, namely Engineering, Production Operations, and Business Operations, prior to reaching an executive level.

Development Product Program Management

The role of development product program manager is typically an executive management position at Aerospace Corporation X. These managers have oversight of all functions, the project plan, and budget for a new product development program until it transitions into low rate production. As a result, the program managers are usually selected for promotion to the position by higher-level executive management, as opposed to being promoted into the position based on seniority or experience. Program managers often have cross-functional experience in Engineering and Business Operations but this is not a requirement. Program managers do not receive an incentive based on program performance, but do receive the general management incentive as well as executive equity disbursements based on their level.

Exempt and Non-exempt Staff

Non-management staff members below level five do not receive monetary incentive distributions. There are non-monetary awards for general recognition and limited opportunities for special disbursements. Promotions within non-management staff usually occur based on seniority, with performance used as a necessary qualifier to achieve promotion at a given level of experience. Personal development and additional education completed during employment

does not directly contribute to promotion or salary assessments.

From the cursory review of the three employee incentive classes, there are a few themes that need to be recognized in advance of analyzing producibility governance or risk management. The first is that promotions are generally either based on seniority or management selection. Therefore, the only way for an employee to be considered for an early promotion is to have visibility within the organization. This focus on visibility can create detrimental incentives. Second, incentives are based on company and individual performance, not product program performance even for program managers. This incentive alignment does not match the level of system governance imposed by EVMS and the performance management system. Finally, cross-functional experience is not a pre-requisite for executive management or product development oversight. A lack of experience doesn't necessarily impair performance, but it contributes to limited perspective in resolving development problems with cross-functional impacts. All of these incentives can be contrary to governance. Producibility risk management must overcome these incentives for effective adoption and monitoring of leading indicators.

3.5.2 Schedule and Milestone Reviews

Schedule is a primary measure of product development efforts within Aerospace Corporation X. This measure is only juxtaposed against product performance, but often takes priority in the absence of clear performance requirement shortfalls. With schedule as a driver, managerial metrics are tailored to oversight of the schedule. This includes not only EVMS task completion measured through the schedule performance index, but also a number of schedule derived metrics including performance-to-plan date differentials, workflow constraints, and on-dock delivery dates. All schedule metrics are usually bracketed within a given phase of development, especially for conceptual design through production engineering and test. This segmented focus is reinforced by technical milestone reviews like concept design review, which in themselves are prerequisites for milestone payments on military product contracts. As a result, the workforce including program management is focused on satisfying entrance criteria for the next milestone review or development phase. The schedule focus does not prioritize work statement growth for risk mitigation and therefore can be an implicit barrier

to new risk management methods. A new approach to risk management must be able to accommodate this schedule focus and function within existing risk management processes, while allowing for earlier and more effective risk capture.

3.5.3 Quality Nonconformances and Inspection

Oversight of the three forms of quality non-conformances discussed previously is accomplished both in the core Quality organization and by executive level management in respective departments. Standard reviews look at quality nonconformance counts, measures of time to resolution, and the cost of poor quality. While touching on several areas of producibility, these reviews promote schedule focus and reactive behavior as opposed to forecasting of future nonconformances or measures of nonconformance avoidance. Drivers of poor quality are identified but, often because of the schedule component in the metrics, are mitigated by additional inspections. Any necessary changes in the driving process or configuration are kept in queue. In addition to creating an inventory of rework, the result is that downstream customers and oversight authorities expect the inspection approaches as a measure of problem resolution. Inspection procedures tend to be retained beyond the actual period of need. Given permanent quality improvements require cross-functional coordination, they need to be reflected in product development statements of work. Unfortunately, the needed improvements are often out prioritized by the implicit inspection and schedule associated with existing work statement, resulting in ongoing impaired producibility.

3.5.4 Engineering Change Management

Product configuration management at Aerospace Corporation X is managed by two separate entities, the change management board within Systems Engineering and the production change management board within program operations. These two entities interface through hand-offs of configuration definition and change effectivity in terms of product units. Within Engineering change management, an engineering change approval process is used to assess the content of engineering changes and approve release of the associated configuration revisions. This process is measured with a schedule focus by examining the time from change initiation

to release of revised configuration. As a result, responsible design engineers are incentivized to complete configuration revisions prior to formal change approval in order to minimize flow in the change approval process.

With revised configuration available, the production change management board is then responsible for assessing impacts to existing processes and for phasing changes into production operations. As changes are released through Engineering with short lead times, it constrains the lead time that production has to assess and plan for the change impact. Process modification is often communicated with limited lead time to manufacturing engineering, preventing necessary process validation. The result is a reinforcing cycle of additional product changes that may be required to achieve product configuration because process constraints were not adequately assessed. New measures of configuration change are needed to allow for a balanced focus on all aspects of producibility for a change.

3.5.5 Problem Resolution

It was previously mentioned that promotion within management is often the result of selection by higher management. It has also been noted that meeting schedule or execution is the focus even when quality nonconformances are identified, and inspection is the bridge that supports product delivery while longer-term improvements are implemented. The result of this environment is implicit value is placed on reactive problem resolution. Individuals recognize that significant visibility and opportunity for responsibility comes with problem resolution, both at the management and staff level. This implicit incentive for solving problems instead of preventing them is a significant issue within Aerospace Corporation X. Work statement and supporting budgets do not typically associate risk management scope within individual teams. System Engineering and Program Management are left to identify and prevent risk for areas in which they do not have visibility. Coupled with inadequate standard work governance for product development and cross-functional communication barriers, early risk identification and mitigation is often stochastic in nature. Reactive risk management is much more common while also having significant impacts on the operating rhythm of the organization. Consistent with the tenets of lean manufacturing, methods are needed that place value on early risk mitigation, visibility, and elimination of wasteful rework.

Aerospace Corporation X is a large organization with inherent complexity and dynamics in culture and politics. The organization is focused on delivery of a high performing product to support customer needs through the efforts of a product and functionally aligned matrix organization. The culture stresses the value of seniority, hierarchal decision-making, and execution to meet product delivery goals. The structure and culture is supported by a competitive positioning system that regiments standard work and feedback in production and business operations. While procedures are well-aligned with goals for operational execution, product development processes and risk management are not as well governed. Barriers to communication exist across functional departments, compounded by a changing oversight with the phase of product development. Incentive structures are misaligned to the organization and individual performance. New methods at the product and program level are needed to improve risk management for producibility in product development. These methods must respect the constraints and dynamics of the organization. For this reason, an analysis of organizational governance will be conducted and the resultant risk management framework will reflect the need for responsibility across disciplines independent of existing incentives.

Chapter 4

Assessing Producibility Control

Producibility can encompass a breadth of product development program attributes. Focus is needed to identify those aspects of the organizational and product system are most pertinent to incurring producibility risk and can have the greatest impact on product performance, program execution, quality, and cost. To achieve this focus, a retrospective case study was undertaken for an ongoing new product development program at Aerospace Corporation X. The program was chosen both due to producibility challenges and breadth of scope in the following development areas:

- Extent of configuration change
- Technology implementation
- Process introduction
- Level of investment
- Dissemination of work statement across operating facilities

This section presents the result of the retrospective study which includes both a review of programmatic performance from concept development through the initial build phase of the program, as well as a baseline producibility control assessment using System Theoretic Process Analysis (STPA). The concluding analysis of causality and identification of organizational assumptions resulting from STPA application to the program will support risk indicator and scoring tool development in Chapter 5.

4.1 Retrospective Study of New Model Development

The development program selected for the retrospective case study involved a military weapons system and integral air vehicle. While the product was marketed as a derivative of an existing product line, the configuration was entirely new and included the following major segments: aerostuctures, dynamic flight systems, avionics/electrical system, propulsion installations, and subsystems. The breadth of configuration change necessitated significant statements of work in Engineering, Production Operations, and Business Operations. For programmatic governance, the previously described military aerospace product development cycle with integral decision gates was invoked by Aerospace Corporation X management. At the time of the investigation, the program was completing the initial build of the flight test articles with concurrent initiation of low rate production activities. The following sections retrospectively review aspects of development program performance not only to expand on the motivation for this investigation, but also to narrow the assessment scope to a typical programmatic structure used to govern producibility risk in Aerospace Corporation X product development.

4.1.1 Program Chronology

A basic measure of product development program performance in aerospace product development is schedule performance. Contract proposal development includes formulation of a baseline program schedule to support work statement estimates by involved functional disciplines, organization resource requirement definition, capital investment, and cost aggregation. The importance of the baseline schedule in military aerospace product development goes beyond its role as an alignment tool for organizational activities. Customer involvement in military product development means the producer is constantly measured against the schedule they defined in the contract proposal, with dependence of both incremental development funding and ultimate production demand on organizational schedule performance. While schedule is a component of producibility for any production system, the contractual dependencies on schedule drive a disproportionate influence on producibility for military aerospace products. The focus can de-incentivize organizational adherence to standard op-

erating procedures and alter the balance of risk mitigation versus development execution activities. For this reason, details of the development schedule are presented to support the retrospective case study of development program performance.

The new product development program examined at Aerospace Corporation X began concept development in 2003 through internal product definition and market assessment activities. The product development effort was commissioned at the request of a specific government customer so requirements development and technology selection occurred in parallel with initial development activity. With the scope of the development effort and inherent technology, a significant number of risk reduction activities were commissioned by the launch customer to mature technology and understand production complexity prior to drafting of the contract proposal. These activities proceeded into the first quarter of the 2005 calendar year, overlapping initiation of proposal development. The expected outcome of the risk reduction activities was not only improvement in technology understanding and the elimination of product performance risk, but a better understanding of the development statement of work to ensure delivery commitments could be maintained over the course of the development cycle. An initial contract proposal and schedule were derived from the findings of risk reduction activities in conjunction with functional discipline statement of work estimates.

Per a review of the resulting proposal schedule, an infusion of additional development funding (acquisition milestone B) was targeted for the third quarter of 2005 with a subsequent contract award at the end of the first quarter of 2006. First flight of the air vehicle, a significant technical milestone, was targeted for the fourth quarter of 2011, with the completion of development and funding for low rate production (milestone C) scheduled for the end of the first quarter in 2013. The five year period between contract award and product first flight, along with a subsequent two year verification and validation period before low rate production, was consistent with typical development estimates for new military products at Aerospace Corporation X. The planned program milestones along with intermediate development and review activities are depicted on the uppermost timeline in Figure 4-1. Annotation has been added to the timeline to denote the six phases of aerospace product development and critical gates that are the focus for producibility risk indicator identification.

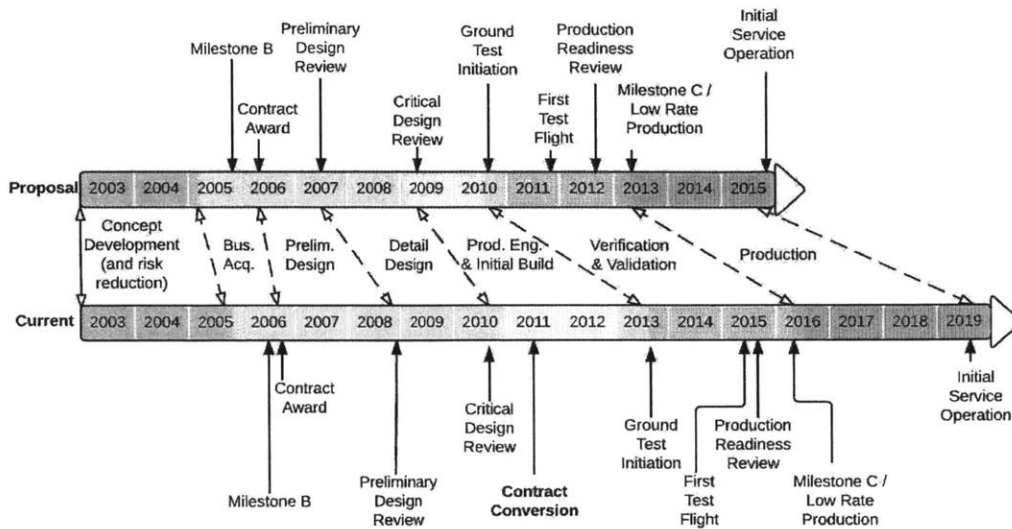


Figure 4-1: Comparison of planned and executed product development schedules for a derivative development program at Aerospace Corporation X.

Comparison of the initial proposed program schedule with the actual period of performance for program development yields a measure of both the success of a organization in understanding the development statement of work and the ability to manage risk throughout the development process. The lower timeline in Figure 4-1 reflects the actual execution of the subject development program. The phases of development have again been annotated to facilitate comparison with the proposed plan. All phases of product development grew in duration compared to the baseline plan, with notable growth for the production engineering and test phase

While the exact reasons for the extension of each phase cannot be deduced from a schedule comparison alone, it can be concluded from the magnitude of growth that there were unforeseen difficulties, likley driven by non-stochastic development challenges. It should be highlighted that in 2011, the customer transitioned the contract from a cost plus format to a fixed price with an incentive option, along with a new statement of work provided by Aerospace Corporation X. This change occurred in direct response to challenges Aerospace Corporation X had encountered during initial product development. The fixed price contract does not provide variable compensation based on the producer level of effort, rather it provides a fixed disbursement to incentivize performance to plan. It also offers as explicit

incentives to improve producibility through rewards of a functional product that meets requirements ahead of schedule. This contract conversion provided the opportunity to address risk after the majority of product definition was fixed, thereby allowing the producer to mitigate uncertainty in the initial proposal and recover from product definition challenges. The driving assumption for timing the conversion after the critical design phase was additional program performance loss will result from production challenges only. This assumption is in error as it does not account for propagating uncertainty related to the compatibility of product definition with the production system. Producibility is a prime measure of the effect of this uncertainty.

The impacted production engineering and initial build phase encompasses physical manifestation of the product from configuration definition and operating procedures. As previously noted, this was the phase with the most significant schedule growth. Similarly, the observed growth in the verification and validation phase is expected if required product performance is misaligned with the capabilities of the integrated product system. In effect, the duration of these two phases are directly proportional to the level of producibility risk not mitigated in prior development phases. An examination of additional program performance characteristics was undertaken not only to attempt to explain the observed schedule challenges, but to help elucidate potential sources of organizational and product risk that need to be considered for early producibility risk management.

4.1.2 Configuration Management

An inflection in program performance was observed between the detailed design and production engineering/initial build phases of the program. The contract conversion that occurred subsequent to the critical design review included a revised statement of work reflecting the relative state of product definition. Review of subsequent configuration changes was conducted to understand difficulty in the transition to build and potential unresolved uncertainty.

A proxy for the maturity of product definition is the release status of digital product definition data or drawings. This is an important metric as release schedules are defined based on future production need dates for hardware and software installation. The variability in product definition release dates was examined in comparison to the baseline release plan.

The distribution of aggregated release data (N=5891) in Figure 4-2 depicts the distribution of date differentials, or difference between the actual release date vs. planned release date, for all program-specific model-based definition. The data shows that configuration release performance was only slightly delayed on average (+9.5 day mean) in comparison to the initial plan. The spread in data (st. dev of 111 days) could signify some difficulty in resolving configuration but it is much less than observed growth in the production engineering phase of the program. Additionally, there was an overall normal distribution to performance with a balance between early releases and late releases.

Assessment of the distribution in isolation would lead to believe that delays on average in defining product configuration were not significant and that a majority of configuration data was available when needed for production engineering. What is missing from this assessment is an understanding of predecessor and successor relationships in the product configuration. Releases are sequenced in engineering planning to support detail completion before assembly and installation drawings within functional areas, but inter-functional and drawing release to suppliers is not as robust. Through conversation with design engineering teams, it was noted that the focus on releases incentivizes sequencing based on complexity, with less complex releases occurring first to drive towards the 95 percent release required for critical design review. The end result is that releases with more complex definition and potentially greater impact on complexity of the product as a whole are delayed until later in the development cycle. Given there are outliers observed in Figure 4-2 at multiple year release differentials, there is a high likelihood that producibility risk is being introduced by a lack of control on release sequencing within the various functional and supplier organizations.

Given the uncertainty introduced by configuration release sequencing, a better metric of the adequacy of product definition data needed to be examined. Cumulative configuration changes in product definition subsequent to the respective initial releases were examined through the third quarter of 2014. Figure 4-3 illustrates the number of cumulative design changes for three major segments of the product, specifically aerostructures, dynamic systems and subsystems. Changes related to engineering and drafting errors have been excluded from the data.

While the relative magnitude of the cumulative changes differs, each segment of the

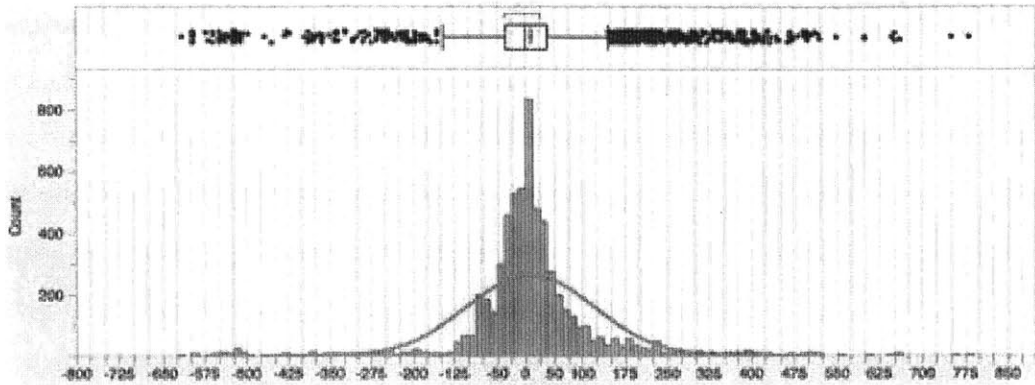


Figure 4-2: Configuration data release performance for a new derivative product program at Aerospace Corporation X.

air vehicle shows continued growth in changes almost three years after the critical design review and initiation of the product build. This information contradicts the proposition that product definition was sufficient at the time of release to support production operations. In the absence of data for configuration quality, the observed change performance is a proxy for quality of configuration definition. Given that configuration drives physical product characteristics, it is also reasonable to assume that change performance correlates to lowered product quality and explicit producibility losses. This relationship with quality necessitates a retrospective review of program quality data which is presented in a subsequent section.

While further investigation into the source of changes is possible, the observed trend is sufficient to conclude that initial product definition lacked maturity to support production, even with growth in the development schedule. Given the continued growth in changes and the interrelationship of product systems, consideration also needs to be given to the fact that singular configuration changes in themselves reinforce additional unanticipated change and catalyze organizational inefficiency. The commonly used metric of release performance versus a baseline plan is not an effective measure of product maturation or risk reduction based on this product development case. Indicators of configuration risk are needed that address both the conjectured reinforcing nature of configuration change and configuration governance within the respective organization. Further investigation is therefore warranted into both the adequacy and implementation of gated product development control within Aerospace Corporation X.

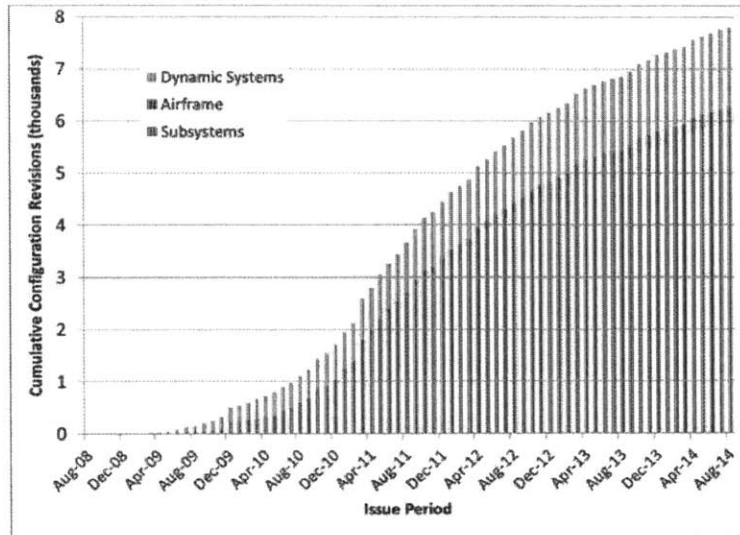


Figure 4-3: Cumulative configuration changes for aerostructures, dynamic systems, and aggregated subsystems over the course of the case study product development effort.

4.1.3 Sourcing Strategy

Another characteristic of a product development program that holds the potential to drive producibility risk is the sourcing strategy for internal vs. external (outsourced) production. Specifically, the added intricacies associated with integration of two separate operating organizations and the scope of production logistics can affect all four aspects of the invoked definition of producibility. With aerospace product development, the inherent complexity in the product creates two distinct options for external procurement of product constituent hardware or software. For constituents that can be easily be defined by physical product definition data or for which the end product producer has unique internal design capability, a build-to-print model is usually invoked. This approach involves communication of limited requirements and product definition data to a supplier who will produce the product with limited internal design and engineering effort. This approach is well-suited for individual parts or sub-assemblies that have limited complexity and for which economies of scale are applicable.

The alternate approach to external sourcing is referred to as design-authority or source-control. This approach involves providing detailed requirements and general engineering specifications to a supplier who then is responsible for full development of product definition

and subsequent production. Design-authority sourcing lends itself to complex sub-assemblies or major assemblies for which the capability of the supplier theoretically exceeds that of the end-product producer. Major assembly suppliers often have significant financial investment in the program and operate as risk-sharing partners.

Given the potential impact of sourcing decisions, a sourcing review by aircraft segment was conducted for the Aerospace Corporation X product development program. Figure 4-4 depicts the findings of this review for the previously examined three aircraft segments: aerostructures, dynamic systems, and subsystems.

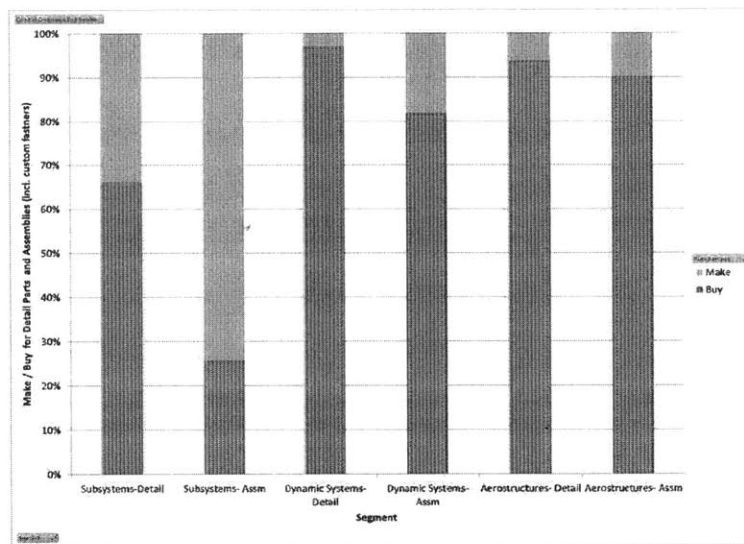


Figure 4-4: Proportion of internally produced (make) vs. externally sourced (buy) detail and assembly configuration for three major segments of the case study product development effort at Aerospace Corporation X.

The presented sourcing data shows that the majority of detail and assembly production for Aerospace Corporation X resides within the supply base for the three depicted aircraft segments. While the proportionality varies, this skewing of production into the supply base is consistent for all aircraft segments and other recent development programs. The balance also follows recent aerospace industry trends for outsourcing and supplier risk sharing. This approach to product sourcing drives the need for not only sufficient supplier capability, but also sufficient capability within internal supplier-facing disciplines.

As a result of the balance of sourcing and observed complexity in the associated supply base, examination of the supply chain interface for product development was assessed to

be critical to capturing indicators of producibility risk. Focus will be placed on the build-to-print outsourcing model as it predominates the outsourcing strategy for the majority of new product development efforts at Aerospace Corporation X. Beyond the focus on supplier interaction, the amount of supplier influence on configuration drives an expectation that leading indicators will also result from measures of supplier capability and performance. This expectation will be reflected in the boundaries of producibility governance examined in subsequent sections.

4.1.4 Earned Value Management

The prior review of schedule and configuration release performance for the subject product development yielded a conclusion that these development program attributes are not adequate measures of either performance or risk. In lieu of just schedule, aerospace program management often leverages Earned Value Management System (EVMS) metrics to assess schedule and work statement execution, in conjunction with cost. For large (\$50 M or greater) U.S. D.o.D. Acquisition Programs, the DoD requires the use of EVMS by contractors to support Acquisition Program Management Office and contracting officer oversight [12]. Given that EVMS measures product development program attributes that are constituents of producibility, a review of EVMS metrics from the case study development program was undertaken. Focus was placed on two indices, the schedule performance index (SPI) and the cost performance index (CPI), which are derived from the cost (in either dollars or labor hours) of completed and planned work per the following formulas:

$$CPI = \frac{BCWP}{ACWP} \quad (4.1)$$

$$SPI = \frac{BCWP}{BCWS} \quad (4.2)$$

where BCWP= Budgeted Cost of Work Performed, ACWP= Actual Cost of Work Performed, and BCWS= Budgeted Cost of Work Scheduled.

The schedule and cost performance indices over the period following contract award through the time of the investigation are depicted in Figure 4-5 at the aggregate air vehicle

level. Annotation is provided to correlate index performance with chronological events from Figure 4-1.

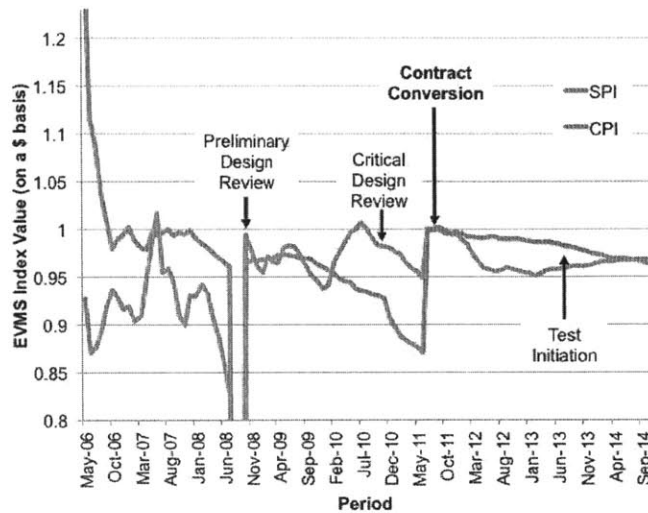


Figure 4-5: EVMS SPI and CPI values for the period of product development from contract award (4th quarter 2006) through October 2014.

With consideration for variation in human performance, a product development effort performing to plan should yield schedule and cost performance indices with stochastic variation around unity. As observed in Figure 4-5, there were significant departures in both the cost and schedule indices from unity from the time of contract award. Beyond reinforcing the observed schedule performance, this information shows that non-recurring program cost control was significantly impacted as milestone reviews were approached. While the inability to accurately capture the required statement of work may be a contributing factor, the magnitude of deviation and divergent trend from unity suggests that there are fundamental program management issues not captured in early-stage planning and risk reduction. Comparison of index performance before and after critical design review (4th quarter 2010), shows an inflection in the rate of loss in cost performance that was more significant prior to initial build activities than for the critical design review. Coupled with schedule volatility, it is assumed seeds of significant producibility risk were planted during this period when configuration was supposed to be mature. Configuration release performance and key performance parameters can assess the impact on product definition, but there is no systematic metric for production risk that correlates with the observed index performance. An assessment of

producibility risk must therefore examine the evolution of governance for production control during design phase activities, well before actual production system implementation. This capture of time-phased program governance was therefore assumed to be a critical attribute to capturing leading indicators for producibility risk.

4.1.5 Development Risk Mitigation

The limited review of program performance has supported a conjecture that risk capture during the subject product development effort was not sufficient to mitigate downstream producibility challenges. While this conclusion may seem premature given the limited data presented at an aggregated air vehicle level, an examination of organizational risk management practice for the case product development effort yields further insight into the effectiveness of development risk management at Aerospace Corporation X. Risk identification by organization and product area was reviewed along with the average duration to mitigation or risk to understand the focus areas for existing risk management processes. Figure 4-6 presents a breakdown of risk by subject area for subject product development case through the 3rd quarter of 2014. Figure 4-7 presents the distribution of the average days to mitigation based on the risk mitigation plan defined for each identified product development risk.

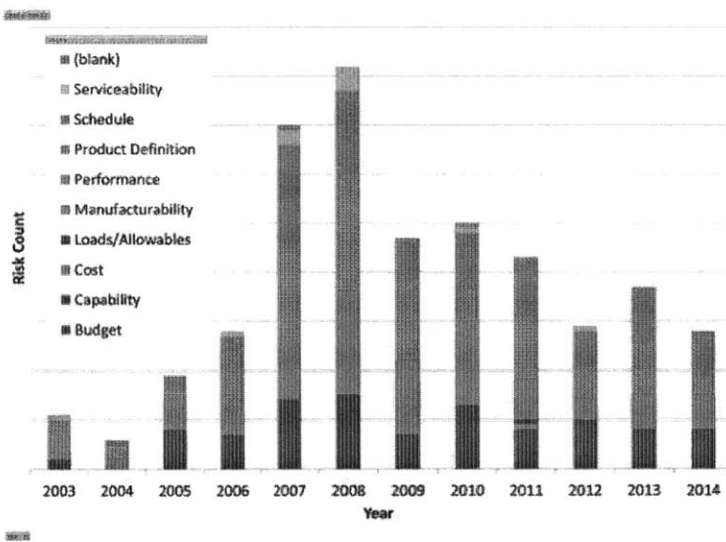


Figure 4-6: Count of opened risks per annum by attribute category for the subject product development program

Examination of the breakdown of risks by category in Figure 4-6 shows that most risks identified within the product development organization are focused on schedule, product performance, and physical product definition. Manufacturability and capability risks are notably overshadowed, especially in 2011 and later years when production engineering and the initial build are underway. The cause of this disproportionate risk item allocation could be due to a number of organizational attributes, including the integration of System Engineering with Design Engineering, focus on product definition, exclusion of functions from the risk management process, requirements changes, or even bias in the risk management governing board for the product program. While likely a result of all of these conjectures, the fundamental fact that risk items do not reflect observed challenges with production operations suggests ineffective producibility governance. Even for the identified risks, resultant impacts on producibility can be considered by examination of risk mitigation activities. The distribution in Figure 4-7 shows that while skewed by long duration plans, mitigation of the identified risks is still taking on average almost three years. Given a proposed design to test schedule of approximately four years, there is a disconnect in the producibility goals of the program and planned execution needed to achieve those goals. A review of organizational interaction can provide insight into both the drivers of the skewed risk focus and how mitigation of risk is managed.

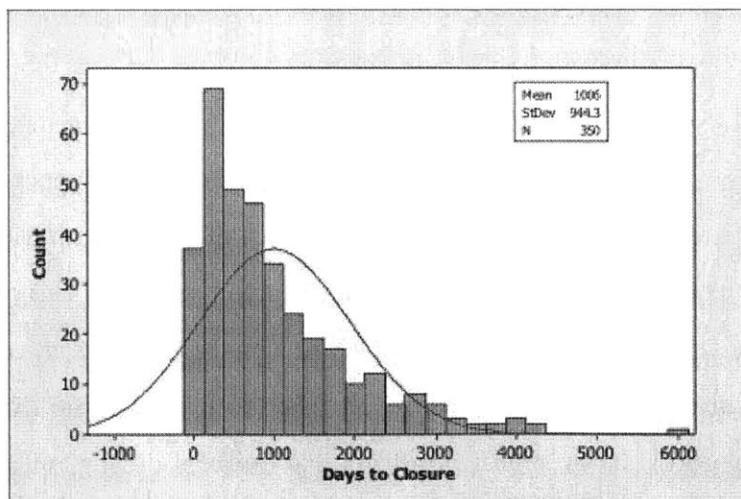


Figure 4-7: Distribution of average time for mitigation of risk (per defined mitigation plan activities) by risk issue period

4.1.6 Initial Build Quality

A final but significant measure of product development program performance and producibility is initial build quality. Consistent with ISO 9001 and AS9100 standards, Aerospace Corporation X has a quality management system that tracks several types of build nonconformances within the production system, as well as errors in product configuration definition and inadequate quality in information transmittal. Assessed build nonconformances range from in-line re-workable workmanship issues to escapes from suppliers to the production line or escapes to the end customer. Each level of nonconformance is documented per standard work and has an associated resolution procedure depending on the severity and impact of the nonconformance. Given that the subject development effort was in the initial build phases with no deliveries to the end user, a decision was made to focus on internal quality issues observed during major or final assembly that affect both physical product definition and cannot be mitigated in-line by an operator without oversight. These quality discrepancies constitute the majority of the quality findings in new product development efforts.

Examination of initial build quality data for the subject product development effort yields not only the magnitude of quality challenges, but more importantly information about disposition of findings and sources of quality loss. Figure 4-8 presents cumulative totals of production nonconformances since the initiation of component production along with categorization of the dispositions of these findings.

The dispositions of quality findings that comprised over half all of dispositions for each period were use as-is or repair as shown in Figure 4-8. This is significant as it shows that there were no significant issues identified with the end product that impaired intended function in a majority of the quality loss cases, but rather some aspect of the product definition or inspection process that were inconsistent with the physical manifestation of the product. The data suggests that there are some elements of the organization or product definition that could be addressed to prevent over half of all quality findings during initial product development. With the same intention, the financial responsibility for quality loss was examined by looking at allocation of quality findings to charging code in Figure 4-9.

The charging information provides additional insight even though some bias or uncer-

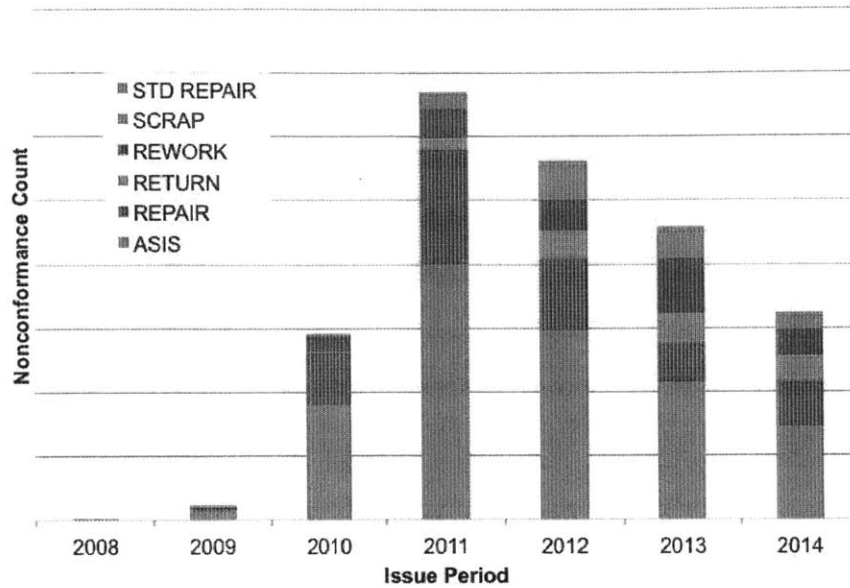


Figure 4-8: Nonconformance totals and dispositions since the initiation of component production for the subject product development case

tainty must be accounted for in financial assignment of responsibility. The data in Figure 4-9 shows that quality losses predominantly were attributed to supplier errors without escape, and then to manufacturing errors. The assignment to supplier error without escape is significant because by excluding the categorization of escape, it signifies that the error was not a physical insufficiency that must be rectified. This supports the use-as-is dispositions in Figure 4-8 and further signifies the opportunity to manage producibility through product definition quality and organizational process.

A final viewpoint on quality loss is garnered from examination of the distribution of quality findings with defect code shown in Figure 4-10. The defect data shows that while the four most prevalent defect sources are related to physical product attributes, they are explicit to product configuration data. It is not surprising to have quality findings attributed to their element of measure, but it does suggest that either there are systemic errors in the manufacturing processes, which are also used for sustaining production, or there again is incompatibility between the as-designed configuration and the physical product. The influence of the product development organization and processes is examined through the techniques proposed in the subsequent analysis to specifically understand both the sources of

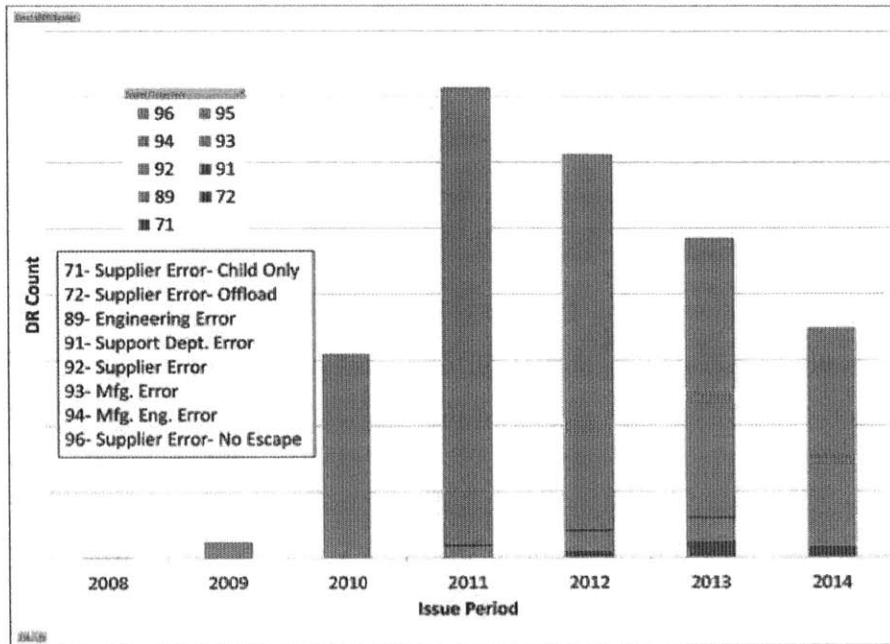


Figure 4-9: Nonconformance totals and charging allocation since the initiation of component production for the subject product development case

incompatibility and significant quality loss, as well as the other attributes of the case study product development program that have been presented in this review.

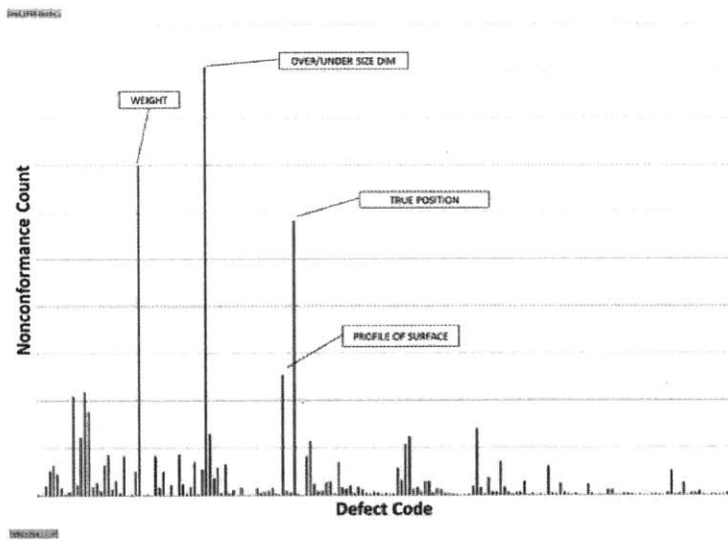


Figure 4-10: Distribution of nonconformances by defect type since the initiation of component production for the subject product development case

4.2 Analyzing Sources of Producibility Impairment

The retrospective review of general measures of product development program performance justifies focus on organizational governance and functional interaction, beyond the product definition process. To investigate the extent of organizational influence on producibility risk and develop a method for assessing risk in future product development efforts, any method invoked needs to capture the complexity and dynamics of not only organizational structure, but of product and process interaction, underlying information flows, and mental models influencing control within the organization. Traditional producibility risk assessments within Aerospace Corporation X rely upon event chain-based process and product failure assessments, using FMEA or FMECA. Numerical assessments would also be conducted on a select basis for critical processes using FTA. As previously discussed, these approaches assume failure within organizational or product components as a nucleation point for system shortfalls, but they are unable to address system complexity-based losses that do not originate from individual constituent failures. System Dynamic Modeling is an alternate and attractive approach that can assess the influence of system complexity on socio-technical performance. This is accomplished through formal modeling and simulation of decision-influenced outcomes in the presence of known exogenous variables. While particularly well-suited for assessing organizational dynamics [31], the formal nature of the modeling can result in both highly complex networks of variables and numerical outcomes that do not reflect the relative influence of constituent components within a given systems [50]. In addition, the need to postulate some feedback loops to achieve mathematical constructs can call into question the relationship of the model to the system it is attempting to replicate [50]. A more tactical approach is desired that leverages actual process and product control structures within a socio-technical system, while still allowing for assessment of underlying human interaction and mental models.

Based on the attributes required in a modeling technique, it was concluded that an extension of techniques from system safety assessment and hazard analysis would be well-suited to address both the influence of socio-technical system attributes and tactical process control on producibility. As previously introduced, System Theoretic Process Analysis (STPA) is a

hazard analysis technique developed specifically for the purpose of capturing aspects of socio-technical system complexity and software flaws that can contribute to safety-related losses in the absence of explicit system constituent failure [31]. The following sections demonstrate a method for extending STPA to assess sources of producibility loss within a socio-technical system. After a systematic investigation of producibility governance for Aerospace Corporation X within the STPA framework, Chapter 5 uses the resultant causal analysis to propose a producibility risk management approach based on existing methods of leading indicator derivation from STPA methods. A discussion of method validation and steps for continued investigation are then discussed in Chapter 6.

4.3 Producibility Losses and Hazards

The first step in STPA is defining the losses and associated driving hazards with respect to the system under investigation. While losses can be readily assigned in a system safety environment where there are tangible negative consequences, it is also possible to define losses as they relate to producibility in product development. The approach taken for this analysis is to define losses associated with each of the four attributes of producibility, as listed in Table 4-1. The losses are intentionally high level and unrelated to the specific system under investigation. The goal is to focus on losses unacceptable to stakeholders, whether internal or external to the organization [31].

Table 4.1: Producibility losses for Aerospace Corporation X assessment

Loss Ref	Producibility Attribute	Potential Loss
L1	Quality	Throughput yield for any fabrication, or assembly process below target %
L2	Product Compliance to Type Design	Product operation or performance is inconsistent with type design requirements or customer expectations as a result of the physical manifestation of product definition
L3	Cost	Exceedence in cost with respect to planned program recurring or nonrecurring budgets
L4	Schedule	Interruption in product flow resulting in a missed commitment to downstream internal or external customer

The defined losses allow for identification of driving hazards that could result in a loss based upon Aerospace Corporation X product development governance and environmental conditions within the development organization. While all of the defined losses for producibility are broad, it can be deduced that cost and schedule losses are potential outcomes of the quality and product compliance producibility losses. Therefore, the scope of the assessment will be narrowed to focus on hazards associated only with quality and product compliance with the type design.

A number of hazards can then be identified in relation to the selected losses to support an assessment of system governance and potential sources of inadequate control. Table 4.2 presents the identified hazards related to quality loss while Table 4.3 presents the hazards defined for the inability to produce a compliant product.

Table 4.2: Hazards contributing to a potential loss of quality

Identifier	Producibility Hazard	Category
PHQ-1	Program manufacturing plan is not defined	Program
PHQ-2	Variation in product definition cannot be controlled with current process capability	Manufacturing & Processing
PHQ-3	Use of new manufacturing process without adequate validation	Novelty
PHQ-4	Aggregation of stochastic variation in assembled product	Complexity
PHQ-5	Process capability does not align with product specifications	Capability
PHQ-6	Skill level of the workforce does not support product definition and process capability	People
PHQ-7	Level of inspection does not adequately assess product attributes	Inspection
PHQ-8	Lack of control in material source	Material
PHQ-9	Lack of understanding of critical system interface control	Criticality
PHQ-10	Tolerances are not satisfied due to inadequate process specification	Requirements
PHQ-11	Production quality does not satisfy lifecycle maintainability demand	Maintainability
PHQ-12	Specified unit cost does not reflect necessary process controls	Design to Cost

Table 4.3: Hazards contributing to a potential loss of product compliance to type design

Identifier	Producibility Hazard	Category
PHP-1	Lack of functional integration during product definition	Program
PHP-2	Incompatibility of product definition with process or assembly capability	Manufacturing & Processing
PHP-3	Insufficient experience with product or manufacturing technology	Novelty
PHP-4	Inability to achieve product definition due to product complexity	Complexity
PHP-5	Production occupational and environmental safety constraints are not reflected in product definition	EH&S
PHP-6	Product definition and process capability is insufficient to produce products compliant with requirements	Capability
PHP-7	Workforce and leadership capability is insufficient to achieve compatibility between product definition and process capability	People
PHP-8	Material characteristics and process compatibility are not understood	Material
PHP-9	Maturity in system requirements is not sufficient to define required functional validation	Requirements
PHP-10	Inability to access and maintain the product	Maintainability

The hazards defined in Tables 4.2 and 4.3 are not failures of the socio-technical system and simultaneously, are not mutually exclusive to failures. The hazards define a undesirable state of the system that in conjunction with environmental conditions can contribute to a loss [31].

In addition to identifying the hazards, categories have been defined to capture hazard consistency between the losses. These categories also apply to schedule and cost hazards not presented due to their subordinate relationship to the assessed hazards. While the definition of these hazard categories is not germane to the STPA extension, they are relevant to the development of a risk management framework and associated implementation of a risk management tool described in Chapter 5.

4.4 Producibility Governance

The next step in assessment of producibility governance is to construct a map of the control structure within the organization that exists to mitigate the defined hazards. In the case of a socio-technical system, this structure is focused on both product development process control and the associated supervisory control within the organization. The previously depicted matrix organization of Aerospace X yields significant complexity in defining an oversight organization for all producibility-related hazards. A general control framework is necessary from which lower level abstractions can be generated to identify all of the integral process and supervisory control loops. Figure 4-11 provides this framework extended from relevant organizational structure to facilitate further analysis of organizational control.

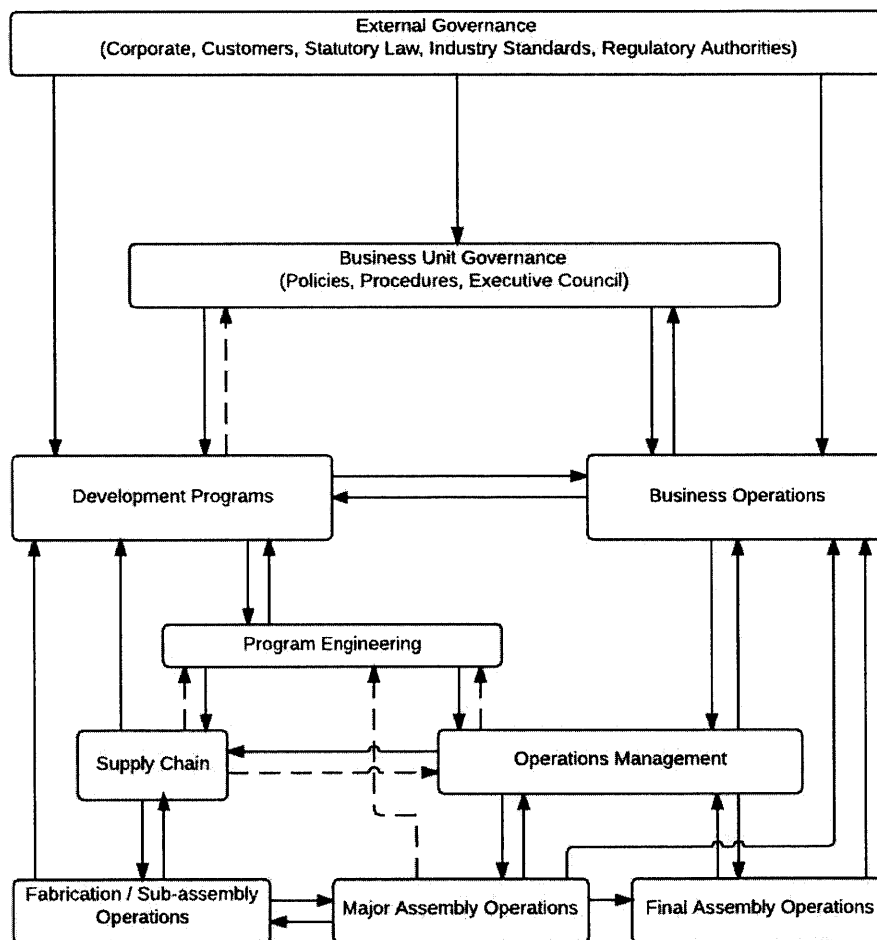


Figure 4-11: Overview control structure for producibility governance within Aerospace Corporation X.

Some of the relationships depicted in Figure 4-11 between controlling elements of the organization are depicted with dashed lines. As the diagram reflects a given state in time for the product development organization, the dashed lines highlight areas where governance is not present during all phases of product development. This is explored further in the subsequent analysis for organizational interfaces and temporal phasing of control.

It is important to step aside and note the boundaries defined for the producibility control system in this analysis. System boundaries define what constitutes a hazard and therefore are subject to the abstraction of the system by the assessor [31]. I have chosen to invoke a broad boundary for the system given the spanning relationship of executive management, the customer, corporate policy, and regulatory authorities down through the hourly manufacturing operators and inspectors. The boundary is also defined based on the case study evidence presented in the preceding retrospective review of a product development effort at Aerospace Corporation X. It was noted that the supply chain had a significant impact on resultant quality and that dissemination of Engineering-generated product definition and requirements occurred as hand-offs to both internal and external Operations. For this reason, a system boundary is selected that envelopes supplier fabrication and component assembly operations, along with the associated control network for supplier oversight of producibility. While it has been noted that suppliers provide both build-to-print and engineered constituents of the final product, a focus is placed on the build-to-print model for component fabrication and sub-assembly given that it is the most prevalent sourcing model across all of the product programs. There is also importance in what is excluded from the system boundary. While individual customer and corporate oversight are included, financial, customer, and labor market controls are not addressed. In addition, the unique relationships with foreign and commercial customer relationships are not presented. This focus drives the control model to also hone in on producibility control for U.S. domestic military programs. This focus is appropriate given the predominance of Aerospace Corporation X sales to U.S. domestic military customers. While focused in the assessment of control, the approach does not prevent expansion to envelope these additional control elements for alternative analyses.

Having defined system boundaries and a high-level, socio-technical control architecture allows for further resolution within the loci of control. In the case of aerospace product

development, the temporal evolution of control must also be considered. This is an important parallel to system safety control where degradation in control is often observed with time. In this case, the organization is evolving with the product, so control is theoretically increasing with time. Both aspects are addressed in the subsequent section to understand phased control and feedback as it relates to producibility governance.

4.5 Phased Control and Feedback Modeling

Examination of producibility governance within the Aerospace Corporation X product development organization requires resolution into the controlling parties and associated configuration management and quality processes. It also requires assessment of the interfaces for transfer of information, the methods of feedback on work products, and the understanding that groups within the organization have of the methods of other internal and external parties. The latter aspects of feedback and understanding of the activities of others, or mental models within the system, are critical aspects to understand the underlying assumptions inherent to the organizational structure. To achieve the necessary resolution, control elements and interfaces must be defined for each of the organizational groups depicted in Figure 4-11. This identification was accomplished through repetitive engagements with a cross-functional team consisting of a management and staff cross-section from the Engineering and Production Operations organizations. While business operations and supplier representation were not present, Engineering and Production representation were chosen for their extensive experience and tenure within in the organization. It was felt that the team was able to provide a sufficient level of insight into the dynamics of product development efforts to facilitate construction of the producibility governance framework. Engagements were supplemented with investigation of defined processes and standard work where applicable to capture all information flows.

Within the boundaries of the defined system for producibility governance, control structures were identified to address producibility control from concept development to the initial build phase of product development. It became evident during the assessment of the evolution of producibility control that it could be condensed into three temporal categories based

on related product development phases: (1) concept development and business acquisition, (2) preliminary and detailed design, and (3) production engineering and the initial build. Using these aggregated categories, control structures were graphically generated as shown in Appendix A. The number of controllers and the complexity of the interactions dictated a more regimented approach to exploring the governance structure. It was decided that an organization architecture design structure matrix (DSM) framework would be adopted for controller interface capture. As noted by Eppinger and Browning, two benefits of a DSM for representing organizations are the ability to concisely capture a large number of organizational entities and their relationships, and extract important patterns of interaction and groupings among those entities [51].

The DSMs invoked in this investigation list the control elements along with macro-categories derived from the macro-structure in Figure 4-11. Control elements are numbered to correspond to the diagrams included in Appendix A. Control elements in the rows are taken as the originator of a control action with the column elements being the recipients. All controllers are listed twice in a row and a column, thereby allowing capture of directed control actions and feedback. The presence of control actions or feedback is represented by an X placed in the intersecting box. Figure 4-12 depicts the DSM for the concept design and business acquisition phases of product development. The DSMs for preliminary and detailed design governance and production engineering and initial build governance are depicted in Appendix B.

The cumulative number of interactions presented in Figure 4-12 and Appendix B signifies the complexity of producibility governance within a large-scale aerospace product development effort. What also must be considered is that necessary but omitted interactions are not depicted from simply completing the mapping exercise. A method is needed to identify omissions that are pertinent across the governing phases. This assessment was accomplished by looking at overlap in the phase control structure DSMs to identify the residence time of control within individual functional areas and across-functions. This overlap also allows for viewing of interactions that are not currently defined for any phase of producibility governance. The underlying assumption invoked for identifying omissions from this approach is that if producibility governance is not present in a given locus of the organization for

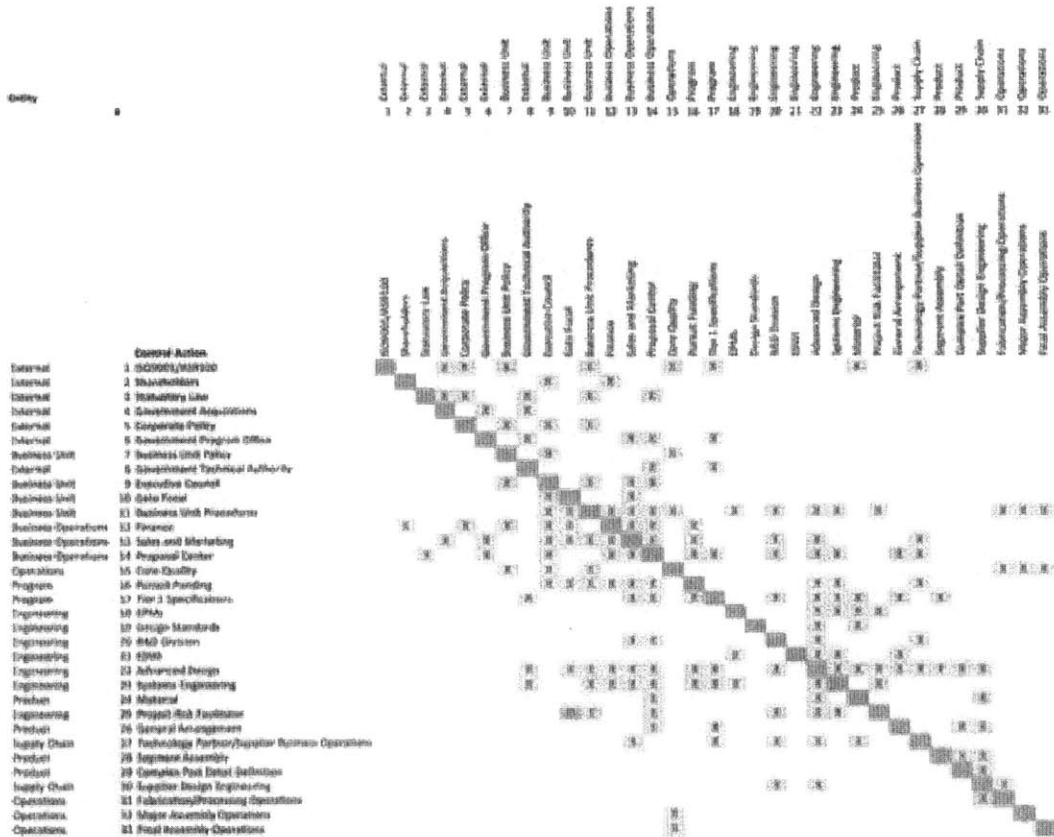


Figure 4-12: Organization design structure matrix for producibility governance during the concept development and business acquisition phases of product development at Aerospace Corporation X.

all durations of the product development effort, it is potentially a source of producibility risk. While other heuristics are valid for narrowing the focus for producibility control, the temporal governance-based approach is most appropriate given that the hypothesis of this investigation involves with the significance of organizational design in producibility risk management.

The phase-overlap DSM assigns a number and associated color based on the frequency of present control actions at a specified interaction. Absent interactions remain blank and were not assessed further. With an understanding of the temporal presence of control interactions during the course of product development, the phasing DSM was then sorted by functional area to allow for a clustering analysis of both interactions internal to functional areas and across functions. Figure 4-13 presents the sorted phase overlap DSM with an enlarged version

provided in Figure B-4 of Appendix B for legibility.

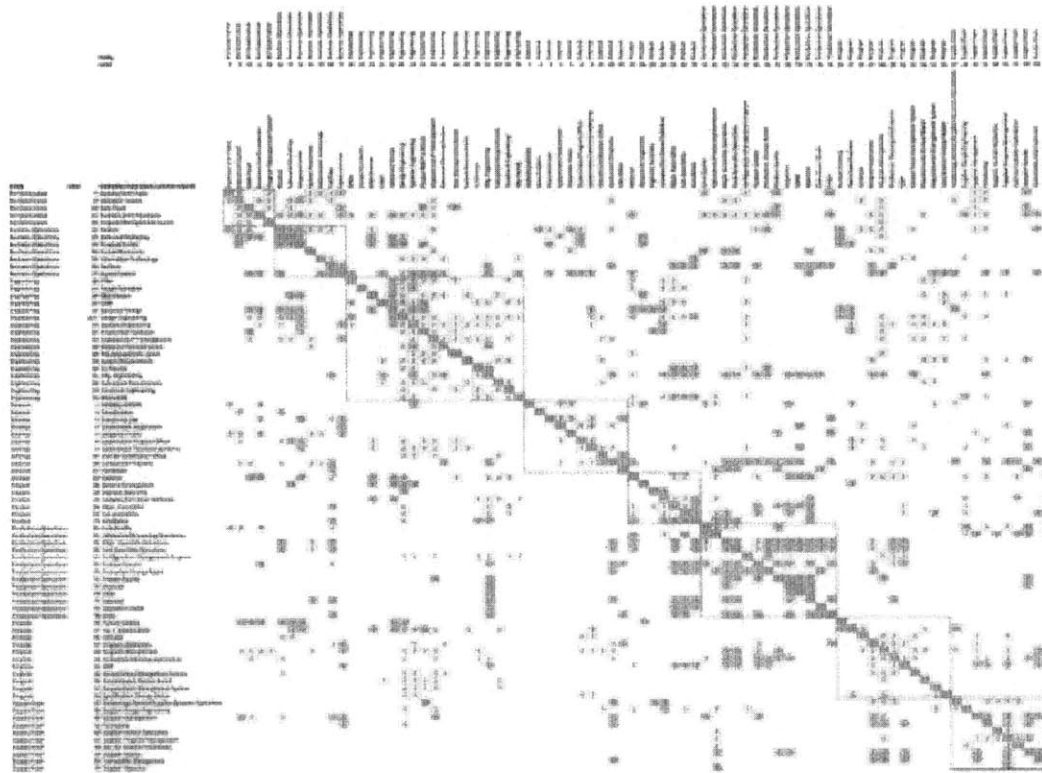


Figure 4-13: Overlap DSM for producibility governance across phases of product development at Aerospace Corporation X (Interaction coloring: green=three phases, yellow= two phases, red= one phase).

Boxes within the sorted overlap DSM define the boundaries of interactions within functional areas. A high level review of the overlap DSM shows that for most areas of producibility governance, oversight or influence occurs for less than the duration of the product development effort as signified by yellow and red coloration. In addition, between functional groupings in the blue boxes near the diagonal axis, there is significant variation in the level of oversight of producibility. This observation speaks to inadequate internal functional interaction in some phases of the program, which by examination of the phased DSMs in Appendix B is at the early-stages of development when risk mitigation is most pertinent. Finally, cross-functional interaction gaps can be observed in the overlapped matrix. Some of these gaps are due to hierarchical levels of control and others may be due the relevance of interactions to producibility. Focus for this investigation was placed on single phase interactions as sources of risk and to limit the scope of analysis. The most comprehensive assessment of

the organization would require a systematic examination of all non-three phase interactions and omissions.

Focusing on single-phase interactions, the next step is to examine the relationships and control actions associated with supervisory control to identify inadequate and temporally omitted control. Given the breadth of interactions that can be examined, the three control cases in Table 4.4 were selected to exemplify the proposed analytical approach. These control relationships cover interactions within a functional area, across functional areas, and with an external organization (supplier).

Table 4.4: Producibility governance cases for method demonstration

Supervisory Control	Process Control	Process
Product Quality	Configuration Management	Config. Change Approval
Product Centers	System Engineering	Risk Management
Design Engineering	Purchasing	Supplier Fabrication

While causation for all missing or inadequate control relationships must be ultimately explored to develop a comprehensive set of producibility risk indicators, the selected interactions provide sufficient resolution to demonstrate the extension of STPA to producibility hazard assessment. The following sections go into the detail of application of STPA to these relationships to determine causality for inadequate control and underlying shaping assumptions.

4.6 Inadequate and Omitted Control

Adaptation of the STPA control model is required for assessment of a purely organizational control system, as opposed to one containing only physical or software-based elements. Both the supervisory and process controller usually represent individual members or teams within the organization in a given function. The controlled process is usually an element of the work breakdown structure for the organization with the controls, actuators, sensors, and displays representing those entities or work products that communicate information between the interfacing parties and process. The model of the controlled process is the respective controlling parties understanding of the related statement of work. The model of automation

for the supervisory controlling party is the respective understanding of how the process controlling party manages the element of the work breakdown structure. Control action generation and the control algorithm are the established processes the respective controllers use to take action when a difference exists between actual behavior and the understood setpoint needed to maintain producibility.

Using the described adaptation, STPA methods are used to assess the selected control relationships in Table 4.4 for inadequate producibility control. The first area of producibility governance for detailed examination is the intra-functional relationship between the Product Quality group and the production Configuration Management Organization. Figure 4-14 presents a model of the supervisory control and process control for this interaction inclusive of control actions and mental models used by the two controlling parties.

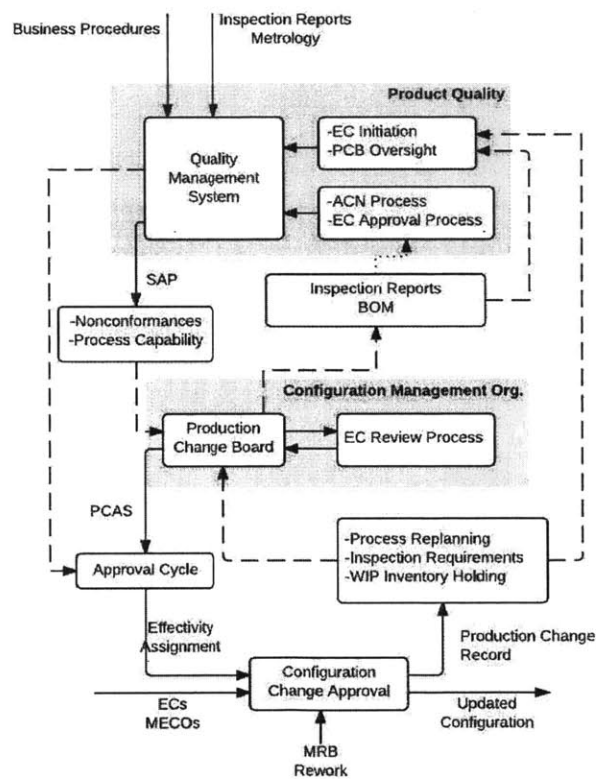


Figure 4-14: Model of supervisory and process control for configuration change management between Product Quality and the Configuration Management Organization.

The first observation that can be made about the control relationship between Product Quality and the Configuration Management Organization is that there are limited communi-

cation paths for quality oversight of proposed changes along with no feedback on the impact of changes to either the Change Management Board or Quality. These communication challenges are represented by the dashed lines depicted in Figure 4-14. In addition, it is observed that as a result of the lack of feedback, there is no reliable input to either the model of the process or the model of Configuration Management organizational operations used by Product Quality to assess the relationship of quality metrics to configuration change. Without yet considering the associated hazards or timing of the control actions, it is apparent that this barrier to oversight will have a significant impact on the early identification of producibility risk. In addition, it will prevent efficient change management when quality shortfalls are known but not being addressed at the time of a configuration revision.

Following the STPA methodology, the next step is to look at the present and missing control actions with respect to specific hazards and determine unsafe modes of control. This is accomplished by determining the condition required for unsafe control to occur under four possible temporal modes. To exemplify this methodology, the missing action between nonconformances / process capability and the production change board will be reviewed, as well as the present Production Change Assessment Sheet (PCAS) action. Table 4.5 provides this assessment of the control actions in relation to the potential resulting hazards identified from those defined in Table 4.2 and Table 4.3.

Table 4.5: Inadequate control assessment for (1) the missing control action between nonconformance reporting and the Production Change Board and (2) PCAS issuance.

Hazard Identifier	Present Control Action	Missing Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Incorrect Timing / Order	Stopped Too Soon / Applied Too Long
PHQ-2		(Nonconformances / Process Capability link to PCB)	Product Quality does not provide relevant nonconformances / process capability when product definition requires variation that cannot be controlled by current processes	N/A	Product Quality provides relevant nonconformances / process capability after product definition is assessed for process compatibility	N/A
PHQ-5	PCAS		Production Change Board does not provide the PCAS when changes are required to capture incapable process in product definition	Production Change Board provides the PCAS when process capability is not sufficient for the configuration	Production Change Board provides the PCAS before process capability has been assessed	N/A
PHP-2		(Nonconformances / Process Capability link to PCB)	Product Quality does not provide relevant nonconformances / process capability when product definition needs to be assessed for a new configuration	N/A	Product Quality provides relevant nonconformances / process capability after product definition is released through the approval cycle	N/A
PHP-2	PCAS		Production Change Board does not provide the PCAS when changes are required to capture incapable process in product definition	Production Change Board provides the PCAS when there is not adequate manufacturing engineering assessment is not requested	Production Change Board provides the PCAS after product definition has been committed	N/A
PHP-6		(Nonconformances / Process Capability link to PCB)	Product Quality does not provide relevant nonconformances / process capability when product definition needs to be assessed for a new configuration	N/A	Product Quality provides relevant nonconformances / process capability after product definition is released through the approval cycle	N/A

From the analysis in Table 4.5, there are key findings in how the missing control action and PCAS issuance can generate producibility hazards. The first is not assessing process capability in either the PCAS approval cycle or the initial determination to pursue a configuration change approval through the Production Change Board. This is a fundamental oversight in the current process in that change assessment after Engineering approval is focused more on production scheduling than understanding if current processes support implementation. While this assessment is supposed to be accomplished through the Manufacturing Engineering organization, there is often not the time or statement of work allotted for assessing process capability beyond process planning for engineering changes. All released configuration, even in product development follows the configuration management process. Therefore, there is not an alternate avenue to understand the impacts of process capability if its not addressed in initial process planning. The second finding relates to alignment of current quality and process shortfalls with configuration release. Because of a lack of feedback on both configuration change and quality, process capability shortfalls that need to be addressed may not be captured in engineering change releases. This can reinforce the iterative cycle of product and process improvement, impairing producibility. Risk indicators need to address both the level of quality feedback and process capability. Chapter 5 will present how these aspects are captured through the extensions of STPA methods.

A second area for detailed examination of inadequate producibility control is the interaction of Product Centers, or specialized areas of assembly and fabrication within the factory, and System Engineering with regards to risk management during product development. Following the same method for modeling the supervisory and process control structure, Figure 4-15 presents the details of control for this interaction.

The relationship between the Product Centers and System Engineering show significant disconnects in terms of producibility governance. Both pathways for Product Center input on producibility risk to the risk management process are incomplete. In addition, feedback inhibition challenges the ability of the Product Centers to understand what risks exist relating to product development and how those identified risks have been mitigated prior to production operations. The role of Process Constraints and the Mitigation Timeline are explored in detail in Table 4.6 for their potential to contribute to producibility hazards.

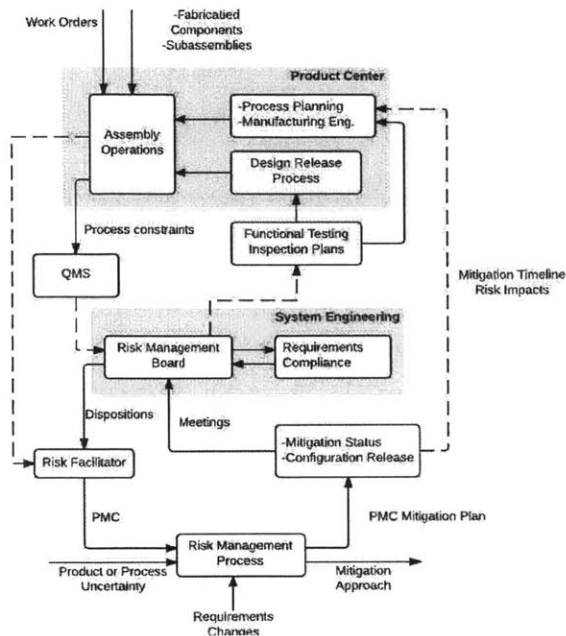


Figure 4-15: Model of supervisory and process control for risk management by the Product Centers and System Engineering.

Several cases were identified in Table 4.6 where restricted information flow on process constraints or risk mitigation timelines from System Engineering could result in a producibility hazard. These assessments support the assertion that early cross-functional communication is needed from Production Operations back into System Engineering to know actual capability in the plant versus what is specified from Facilities or prior programs. The communication has to be bi-directional, not just providing the production constraints to support design. Operations assessment and risk mitigation cooperation are needed to ensure that any identified configuration risk is understood and mitigated. This is a critical element to producibility governance in product development and yet probably the most overlooked due to siloed functional operations. These particular findings are consistent with conversations during the supporting practicum in which early-development Engineering teams had no awareness of quality issues in the factory. They believed the issues had been resolved years early through risk mitigation plans involving laboratory testing.

Table 4.6: Inadequate control assessment for dissemination of (1) Process Constraints and (2) risk Mitigation Timelines.

Hazard Identifier	Present Control Action	Missing Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Incorrect Timing	Stopped Too Soon / Applied Too Long
PHQ-1,PHQ-7,PHP-1,PHP-3,PHP-5,PHP-7		Mitigation Timeline	Risk Management Process does not provide the Mitigation Timeline when product centers need to adjust the manufacturing plan to accommodate	Risk Management Process provides the Mitigation Timeline without gathering impacts to production operations	Risk Management Process provides the Mitigation Timeline before assumptions for assessment are validated	Risk Management Process stops providing the Mitigation Timeline before production system is established for at rate production
PHQ-2,PHQ-3,PHQ-6,PHQ-11,PHQ-12,PHP-6		Mitigation Timeline	N/A	Risk Management Process provides the Mitigation Timeline without accounting for process capability	Risk Management Process provides the Mitigation Timeline after process capability has frozen	Risk Management Process stops providing the Mitigation Timeline before production resources and labor are secured
PHQ-4,PHQ-5,PHQ-6,PHP-2,PHP-3,PHP-6,PHP-7	Process Constraints		Assembly Operations does not provide Process Constraints when process incompatibility risk exists for configuration	N/A	Assembly Operations provides Process Constraints after risk mitigation plans are defined	N/A
PHQ-9,PHQ-10,PHQ-12,PHP-4	Process Constraints		Assembly Operations does not provide Process Constraints when product configuration is being assessed	N/A	Assembly Operations provides Process Constraints after product configuration is defined	N/A

A third area for detailed examination of inadequate producibility control is the interaction of Design Engineering with Purchasing to release configuration for supplier fabrication operations. Figure 4-16 depicts the relevant control actions, models, and relationships within this loci of the producibility governance system.

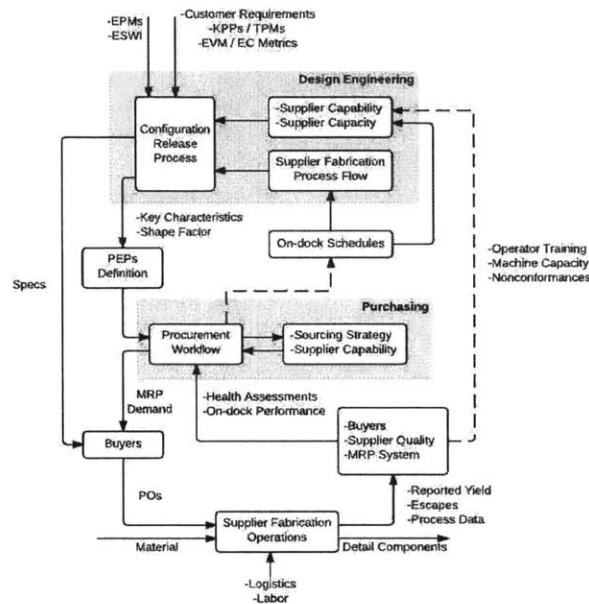


Figure 4-16: Model of supervisory and process control for release of configuration for supplier fabrication by Design Engineering and Purchasing.

While the supervisory control structure in Figure 4-16 is more complete than in the previously presented cases, there is still the presence of missing feedback between Purchasing and Design Engineering, as well as between fabrication reporting and Design Engineering. The potential gap resulting from this inadequate feedback prevents dissemination of supplier process and operational capability to Design Engineering. This in turn can reinforce the potential incompatibility of product definition with supplier processes, thereby contributing to quality loss and deficient producibility. The control actions of measuring On-dock Performance and disseminating Machine Capacity (rate and physical) from the supplier are explored in more detail in Table 4.7 to exemplify the potential contribution of this control relationship to producibility hazards.

Table 4.7: Inadequate control assessment for (1) the missing control action of machine capacity between the Buyer and Design Engineering and (2) On-dock Performance.

Hazard Identifier	Present Control Action	Missing Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Incorrect Timing / Order	Stopped Too Soon / Applied Too Long
PHQ-4,PHP-2	On-dock Performance		Supplier quality does not provide on-dock performance when insufficient quality is achieved by supplier	Supplier Quality provides on-dock performance when supplier achieves rate but has a low yield	N/A	Supplier Quality stops providing on-dock performance before at rate production is required
PHQ-5		Machine Capacity	Buyer does not provide machine capacity when the rate or yield is constrained by product definition and rate increases are forthcoming	N/A	Buyer does not provide machine capacity before product configuration change or rate increase	N/A
PHQ-6	On-dock Performance		Supplier quality does not provide on-dock performance when capability is insufficient to achieve quality at rate	Supplier Quality provides on-dock performance when supplier achieves rate but has a low yield	Supplier Quality stops providing on-dock performance before acceptable quality is achieved	Supplier Quality stops providing on-dock performance before at rate production is required
PHP-3,PHP-4,PHP-6,PHP-7		Machine Capacity	Buyer does not provide machine capacity when new configuration at a given rate is required	Buyer does not provide machine capacity for an old configuration or development rate only	Buyer does not provide machine capacity before product configuration change or rate increase	Buyer stops providing machine capacity before new product introduction

The phasing analysis for the missing control action of Machine Capability and the present control action of On-dock Performance again highlight potential to overlook capability and quality, this time in the supply base. Supplier quality and the buyers traditionally focus assessments on finished goods delivery to support assembly customers. Either because of constrained visibility or directed focus, the assessments of suppliers do not address operating performance drivers such as capacity and capability. Given the missing interface between Design Engineering and the parties with oversight of supplier operations, the absence of this information will not be realized during the configuration definition process.

The assessment methods presented should be extended to assess all limited or absent control actions identified from the overlap DSM. This approach was taken as part of the associated practicum supporting this investigation with success. The extent of the analysis is not presented as it is repetitious to the examples above and exposes company proprietary process information. With areas of inadequate control identified, the next STPA-directed step is to examine causation and associated system design assumptions. This step will be essential in identifying risk indicators for early stage development and presenting a new approach to producibility risk management.

4.7 Assessment of Causation and Shaping Assumptions

For the three cases of supervisory control presented, several conditions were determined whereby control actions could contribute to producibility hazards. The next step preceding indicator development is to continue the STPA extension by stepping through these control conditions and understanding what causal factors in organizational governance can result in the identified conditions. From the casual factors, organizational assumptions that shape the control structure are identified. These assumptions will subsequently be used to assess governance at the earliest phases of product development to identify producibility risk. This methodology for risk indication follows the work of Leveson who builds upon the assumption-based planning methods originally implemented for mid and long term defense planning [43].

Causality and shaping assumptions associated with inadequate control in the governing relationship between Product Quality and the Configuration Management Organization

are identified in Table 4.8 for the corresponding inadequate control actions highlighted in Section 4.6. In this case, causation is attributed to insufficiency in both the understanding of production processes during pursuit of the engineering change control process and execution of the review process using the production change assessment sheet (PCAS). Assumptions underlying these deficiencies relate back to reliance of individual functions on the quality management system and configuration management processes to capture necessary information for product development. This assessment highlights a fundamental risk with over-reliance on procedures and organizational standard work. While procedures and standard work may be defined to capture comprehensive processes at a point in time, the maturity of the processes can lag reality due to resource focus on the current projects. Gaps develop in standard work that are never captured unless identified through an audit process. In the case of Aerospace Corporation X, there were significant durations without review of currency for standard work. For knowledge management within product development, this can be critical. The next team will rely upon the established methods and best practices of those who preceded them based on the assertion that standard work provides the most efficient and validated method of accomplishing tasks.

A second assumption underlying this limited case of insufficient control is timing of Production Change Board implementation. The assumption that configuration management within Engineering will address forming decisions for production prior to actual production process implementation is not supported in any procedural methods. In an Engineering-centric environment, it is understandable that Operations would expect these considerations to be made early in the configuration definition process. Unfortunately, without an understanding of cross-functional work statement, this aspect of decision processes is lost in Engineering. From this limited presentation of assumptions underlying inadequate control between Product Quality and Configuration Management, it is evident that significant risk is incurred without proper organizational process review criteria and without agreement across functions on bounds of responsibility. Management of best practices and the configuration change review cycle will need to be addressed in risk indicator development.

Table 4.8: Causality and shaping assumptions for presented inadequate control actions in the interaction of Product Quality and the Configuration Management Board

Hazard Identifier	Inadequate Control Action	Causality	Shaping Assumptions
PHQ-2	(Nonconformance / Process Capability link to PCB)	Product Quality process and control models for engineering ACN and EC process do not reflect variability in (1) communication between design engineering and manufacturing engineering and (2) the level of familiarity with sources of process data within engineering design and manufacturing teams	All company operating procedures tree up to the quality management system. ACN and EC approval cycles within engineering are defined to include manufacturing engineering oversight. Product Quality relies on the familiarity of the manufacturing engineering team with quality reporting procedures to incorporate this information into process assessment and definition.
PHQ-5	PCAS	The Production Change Assessment Sheet (PCAS) does not adequately address producibility and is not consistently invoked for first-time release of configuration in product development. The worksheet is focused on production change cut-in sequencing with check boxes for assessments of "Illities". Coupled with schedule pressure on approvers, adequate consideration for or information on producibility impacts is not captured.	The PCAS process relies on change interpretation by approving functional disciplines. There is not standard work associated with the assessment of producibility impacts for either development or sustaining manufacturing engineering effort.
PHP-2	(Nonconformance / Process Capability link to PCB)	Product Quality process and control models for engineering ACN and EC process do not reflect variability in (1) communication between design engineering and manufacturing engineering and (2) the level of familiarity with sources of process data within engineering design and manufacturing teams	All company operating procedures tree up to the quality management system. ACN and EC approval cycles within engineering are defined to include manufacturing engineering oversight. Product Quality relies on the familiarity of the manufacturing engineering team with quality reporting procedures to incorporate this information into process assessment and definition.
PHP-2	PCAS	Application of PCAS processes are inconsistent during initial product definition due to the phase introduction of the production change board approval process.	Production change board implementation occurs during the late detail design or production engineering phases of development. This timing is driving by production work statement and resource considerations. It is assumed that prior to this period, manufacturing engineering is consulted as part of the configuration release process.
PHP-6	(Nonconformance / Process Capability link to PCB)	Product Quality process and control models for engineering ACN and EC process do not reflect variability in (1) communication between design engineering and manufacturing engineering and (2) the level of familiarity with sources of process data within engineering design and manufacturing teams	All company operating procedures tree up to the quality management system. ACN and EC approval cycles within engineering are defined to include manufacturing engineering oversight. Product Quality relies on the familiarity of the manufacturing engineering team with quality reporting procedures to incorporate this information into process assessment and definition.

Similarly, causation and assumptions shaping the interaction of Product Centers with System Engineering as part of the risk management process were also explored. As shown in Table 4.9, causation of inadequacy in the control actions of the Mitigation Timeline definition and Process Constraint Identification are a function of reliance on siloed functional expertise within the organization. Manufacturing Engineering is tasked with an understanding of all production constraints and risks in early product development, as well as methods to mitigate these risks. This assumption by the Product Centers and System Engineering assumes Manufacturing Engineering has an understanding of all process requirements for the new product and has involvement in the IPT risk management process. In both procedure definition and reality, Manufacturing Engineering has no defined involvement in the current state of the risk management process, very little oversight of new production process development, and little power within the Design Engineering IPT as discussed in Chapter 3. Therefore, it is expected that the noted assumptions would preclude inadequate organizational control and need to be captured in an indicator process.

Table 4.9: Causality and shaping assumptions for presented inadequate control actions in the interaction of the Product Centers and System Engineering.

Hazard Identifier	Inadequate Control Action	Causality	Shaping Assumptions
PHQ-1, PHQ-7, PHP-1, PHP-3, PHP-5, PHP-7	Mitigation Timeline	There is no established process for product and process risk communication to production operations. Risk management inputs and assignment are confined to Engineering and Program Management	Production operations and resources do not have statement of work at early stages of product development.
PHQ-2, PHQ-3, PHQ-6, PHQ-11, PHQ-12, PHP-6	Mitigation Timeline	The risk management process is not capturing process capability risks beyond those associated with new manufacturing techniques.	(1) Manufacturing engineering will provide process risks if required, (2) Existing manufacturing techniques have process control data that can be interpreted so risk mitigation is not required
PHQ-4, PHQ-5, PHQ-6, PHP-2, PHP-3, PHP-6, PHP-7	Process Constraints	There is no established development process for process risk assessment or communication from production operations to system or design engineering.	Manufacturing engineering will provide process risks if required.
PHQ-9, PHQ-10, PHQ-12, PHP-4	Process Constraints	There is no established development process for configuration assessment by production operations to system or design engineering.	Manufacturing engineering will be responsible for identifying build risk during EC release process.

Finally, the source of inadequate control was considered for the interaction of Design

Engineering and Purchasing in Table 4.10. Causality of producibility control loss in this interaction is primarily due to a misunderstanding of cross-functional information needs and work statement. Supplier quality and buyers believe that technical process information required for product configuration is received as part of the request-for-proposal (RFP) and contracting submittal packages. Focus by these groups is then placed on supplier rate performance, as opposed to yield or capacity at a level of fidelity required by Design Engineering and Manufacturing Engineering to understand process capability. The assumptions that managing normal production constraints of on-dock delivery and quality escape containment support producibility governance is valid, but it misses the more critical foundations of supplier producibility that are fixed in early stage process planning and development. This oversight can be directly attributed to assumptions with the Operational disciplines regarding Design Engineering engagement with Supplier Engineering and Supplier Operations during early product development. For this reason, feedback control must not be the only area of the supervisory relationship assessed for producibility risk. Forward communication of specifications as part of the configuration management process must be examined for inadequacy that can drive risk into process control of supplier fabrication operations.

Table 4.10: Causality and shaping assumptions for presented inadequate control actions in the interaction of the Design Engineering and Purchasing

Hazard Identifier	Inadequate Control Action	Causality	Shaping Assumptions
PHQ-4,PHP-2	On-dock Performance	Supplier health assessment process focuses on (1) supplier delivery performance and (2) supplier-provided escape information	The critical aspect of supplier performance affecting build quality is the receipt of parts when needed by major and final assembly.
PHQ-5	Machine Capacity	Buyer either (1) does not have an understanding of supplier process capacity or (2) assesses adequacy of capacity without an understanding of technical constraints in the process	RFP and contractual agreements reflect supplier capacity constraints; supplier was selected to be able to meet demand
PHQ-6	On-dock Performance	Supplier health assessment process focuses on (1) supplier delivery performance and (2) supplier-provided escape information	RFP and contractual requirements dictate a robust supplier quality management system; all quality findings will be captured and addressed per the outline system
PHP-3,PHP-4,PHP-6,PHP-7	Machine Capacity	Buyer either (1) does not have an understanding of supplier process capacity and (2) there is no managed interface between the buyer and Design Engineering	Supplier proposals reflect supplier capability; Engineering IPT management has visibility to technical responses to proposals

Three examples of supervisory control within the Aerospace Corporation X product de-

velopment environment have been used to demonstrate the extension of STPA methods for identification of inadequate producibility governance. This approach is able to interrogate the sociotechnical structure within the product development organization and is not constrained by product features or the schedule of the product definition cycle. The expanded scope allows for identification of more producibility effectors, but also allows for earlier assessment when mitigation of producibility loss drivers is possible without significant rework.

4.8 Summary of Inadequate Control Assessment

The extension of STPA to producibility hazard analysis demonstrated in the above examples elucidates inadequacy in both feedback and mental models that contribute to producibility governance during product development. While a complete review of all control actions discussed with the supporting cross-functional team cannot be captured, a cumulative count of identified inadequate and omitted control actions is presented by organizational entity in Table 4.11. It can be observed from the aggregate count that a higher number of inadequate and omitted control actions were observed within the organization in comparison to the product level. While the imbalance of control inadequacy toward the organization is not sufficient to determine a statistically significant relationship, it does highlight the need for extensive improvement in producibility oversight and support the proposition of this investigation. Subsequent methods presented in Chapter 5 will demonstrate how risk indication can be derived from associated assumptions and discuss quantitative approaches to support affirmation of the organizational influence hypothesis.

Table 4.11: Aggregated counts of identified inadequate and omitted control actions by controlling entities across all phases of governance

Controlling Entity	Hazardous Control Actions	
	Omitted	Inadequate
External Governance	2	28
Business Operations	5	54
Production Operations	3	80
Engineering	1	53
Supply Chain	4	37
Product	3	29

Comparison of the inadequate control assessment conducted using an extension of STPA methods to existing audits of organizational governance would be desirable. Unfortunately, the case study organization of Aerospace Corporation X did not have assessments, such as product development process FMEAs or productivity metrics, that could be leveraged for this comparison. Comments on opportunities for operational data structures to support method validation are presented in Chapter 6.

4.9 Limitations of Existing Program Metrics

The limited scope assessments of producibility control presented above highlight why phased product development program metrics like design releases, earned value management, or on-dock performance do not capture or mitigate development program risk. These metrics do provide information about the baseline statement of work completion, resource forecasts, and work-in-progress, but are ultimately limited by the stage-gate approach to aerospace product development. Metrics and indicators for organizational integration and development system maturity are needed independent of program chronology. For this reason, this investigation not only presents new methods of assessing producibility risk, but also will present indicator identification methodology and describe implementation of early-stage producibility risk assessment.

Chapter 5

Indicator Framework for Managing Producibility Risk

Producibility governance has been assessed for inadequate and omitted areas of control, as well as supporting flaws in feedback and mental models underlying insufficient governance. While useful as a retrospective assessment, a method is needed to leverage the assessment of product development structure for mitigation of future product and programmatic risk. In addition, any method must align with existing risk management practices to be effective in implementation and application within the organization. This section of the investigation provides a method for defining leading indicators of risk based on the extension of STPA for producibility hazard analysis. The identified leading indicators are then used to develop a formal framework to support a leading indicator monitoring program and integration with existing risk management practices. Finally, validation of the defined leading indicators against organizational performance is attempted within the bounds of available operational data.

5.1 Definition of Leading Indicators

Identification of areas of inadequate control for producibility along with the causal analysis presented in the prior chapter form the foundation for identification of leading indicators for associated producibility risk. While extrapolation of likelihood and consequence, the two

aspects of risk, requires consideration for organizational and development program-specific attributes, identification of leading indicators from the STPA-based approach allows for active risk recognition. As presented by Leveson [43], leading indicators for safety risk can be drawn from assumptions underlying engineering decisions and coordination design. The following assumption types are presented by Leveson to support indicator identification:

1. Assumptions about the system hazards and the paths to (causes of) hazards.
2. Assumptions about the effectiveness of the controls, that is, the shaping and hedging actions, used to reduce or manage hazards.
3. Assumptions about how the system will be operated and the environment (context) in which it will operate.
4. Assumptions about the development environment and processes
5. Assumptions about the organizational and societal safety control structure during operations
6. Assumptions about vulnerability or severity in risk assessment that may change over time and thus require a redesign of the risk management and leading indicators system itself.

Following the approach of extending STPA methods for assessment of producibility governance, the example assessments in Chapter 5 present shaping assumptions that were generated in the context of the above assumption types. Beyond the printed examples, assumptions were formulated as part of the larger organizational assessment for those inadequate control actions to which the organization was deemed most vulnerable. According to Leveson [4-5], assumptions for system operation and interaction with its environment fall into the following three categories:

1. The models and assumptions used during initial decision making and design are correct.
2. The system will be constructed, operated, and maintained in the manner assumed by the designers.
3. The models and assumptions are not violated by changes in the system, such as workarounds or unauthorized changes in procedures, or by changes in the environment.

In the context of producibility governance, the three assumption categories above encapsulate product development program management activities and organizational standard work for procedural governance. Decision-making is a management function in this case that must be considered from all functional perspectives, accounting for bias and discipline-centric

knowledge. It has been shown through the causal analysis that the highlighted assumptions have flaws based on phasing of producibility oversight and inadequate feedback in actual product development program practice. Therefore, following the guidance of Leveson, the next step is to identify indicators for vulnerable assumptions that can be measured at a given interval and can support mitigation action. For the inadequate control actions exemplified in Chapter 5, this approach allows derivation of the indicators in Table 5.1 from the underlying shaping assumptions.

Table 5.1: Leading indicators for inadequate producibility control during the product development cycle

Inadequate Control Action	Assumption-based Indicators
(Nonconformances / Process Capability link to PCB)	Revised EC documentation with manufacturing engineering summary of process-related quality issues
PCAS	(1) Inclusion of manufacturing engineering process pre-planning in change assessment package (2) 1:1 change board assessments between engineering and operations
Mitigation Timeline	(1) Resource-tracking and management system for operations (2) Process control data review requirement for configuration release
Process Constraints	(1) Process control data review requirement for configuration release (2) Mandatory manufacturing engineering representation on risk assessment boards
On-dock Performance	(1) Supplied-component specification template inclusion of supplier capability assessment framework (2) Contractual deliverable for quality history for similar supplied components
Machine Capacity	(1) Supplied-component specification template inclusion of supplier capability assessment framework (2) Machine utilization history and forecast in supplier data package

The assumption-based indicators identified are tangible and measurable, whether by their presence or by quantitative valuation. Further definition of indicators in this manner for all vulnerable assumption allows those responsible for design of product development organizations to capture complexity of the socio-technical system in the risk management structure. Implementation of a monitoring program for these indicators will facilitate in-

creased risk management efficacy, if supported by a standard approach to implementation and dissemination of information. To support this need, a risk management framework for leading indicator monitoring will now be proposed that leverages the STPA basis of the control assessment and aligns with standard approaches to aerospace product development risk management.

5.2 Producibility Assessment Tool Development

Leading indicator identification allows for early warning and detection of potential risks if implemented within the framework of an effective risk management system. To facilitate implementation and monitoring of leading indicators, it is proposed that a knowledge-based framework that builds on standard aerospace risk management practice be implemented on product development programs to facilitate producibility risk capture. The method invokes subjective assessment, by tenured subject matter experts, of producibility control action-based categories. Assessment is guided by a scale structured from the assumption-based indicators as outlined in Table 5.2.

Table 5.2: Alignment of STPA elements with producibility assessment tools structure

STPA Elements	Tool Structure
Hazard Groups	Factors
Control Actions	Categories
Indicating Assumptions	Rating Scale

The extent of inclusion of control actions within the tool is based on a balance of vulnerability in associated governing assumptions with a manageable scale of the assessment for execution by subject matter experts. The scale for scoring is defined numerically from one to five in integer increments, corresponding to increased vulnerability of violation in the governing assumptions, and thus increased risk. Aggregate numerical scoring is incorporated through grouping of categories by associated hazards or factors, and then using simple averaging within the factors and a weighted average for aggregation at the product entity level. While this simple approach to aggregation is not robust in capture of outlier scores, the intent of this framework is to provide a common qualitative platform for discussion of

producibility risk at the control action, or category level. Aggregate scoring facilitates initial definition of a risk likelihood that can be adjusted based on organizational standards, as described in the subsequent section. The discussion at the category level is facilitated by individual presentation of category ratings using radial visualization, grouped by factors. A higher-level presentation of average scoring at the factor level is also depicted in radial format. Figure 5-1 provides a notional format for the output of the assessment process. Radial presentation of category scoring is shown along with factor-level aggregation.

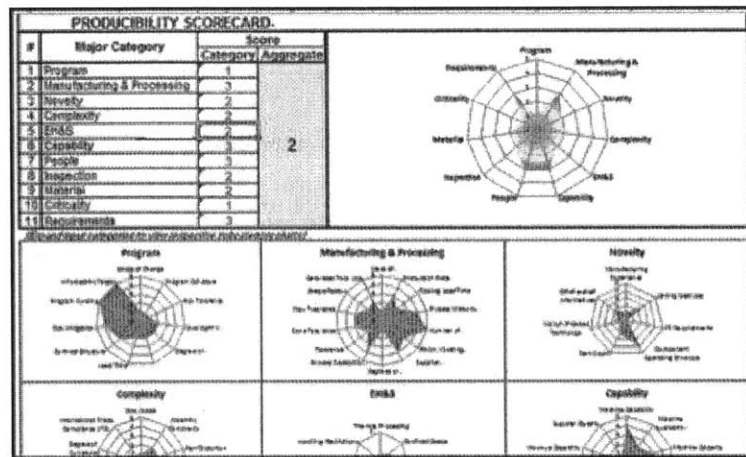


Figure 5-1: Example format of producibility assessment tool platform for leading indicator monitoring and dissemination of risk.

The intent for application of this assessment framework is for expert reviews to be conducted at the level of singular components or assemblies in the concept or business acquisition phase of the program, prior to the availability of detailed product definition. Subsequent assessments shall be conducted in support of stage-gate product development review activities. This early and phased application of leading indicator monitoring will not only allow for early understanding of where assumptions underlying organizational governance for producibility are vulnerable, but also allow for the desired early mitigation and resource allocation necessary to mitigate program risk beyond the product definition space. It is expected that for product engineering or feature-based aspects of producibility, traditional methods of assessment will complement leading indicator monitoring as part of the risk mitigation effort. The value and uniqueness in this framework lies in the assessment of coordination aspects of producibility risk, allowing for the modification of governance or implementation of a different

part or assembly level strategy that will improve on the affected aspects of producibility.

5.3 Factor Weighting and Likelihood Translation

For the purpose of organizational implementation, it was stated that hazard group, or factor, scoring is aggregated within the proposed scoring system using a weighted-average approach to support an initial likelihood correlation. This aggregation is understood to introduce the same concerns previously outlined in literature for quantitative risk assessment, as well as computational bias to a linear continuum of scoring for a potential nonlinear risk distribution. Even with this shortcoming, the aggregation is promoted to allow the interfacing of leading indicator monitoring with existing organizational risk management methods. The numerical scale for assessment of one to five was chosen based on the likelihood range for the case study organizations risk management methods. With the availability of operating data for producibility event occurrence, such as quality defect rates or problem reports, response surface methodology can be used to translate this scoring to a statistically significant likelihood of occurrence for assumption violation. Producibility outcomes supporting this statistical approach to translation must reflect the likelihood of loss occurrence. The next section examines the use of quality defect rate as the basis for factor weighting. With the ability to translate producibility indicator scoring to statistically significant likelihood, a direct interface is provided to organizational risk management that can be supplemented by program consequence definition. The quantitative error introduced in the translation is no more significant than potential score biasing in the proposed expert scoring framework. In addition, the value in this translation is not in the absolute likelihood, but rather the structured presentation of risk for further consideration and management by the product development organization.

5.4 Validation of Programmatic Response

The ability to assess the efficacy of the developed approach to producibility risk capture is challenged by the duration of the aerospace product development period and life-cycle

of typical aerospace product development. The period of the supporting practicum was insufficient for formal validation of the proposed leading indicator program and associated risk mitigation methods, but three measures of indicator efficacy were explored: retrospective correlation of indicators with producibility outcomes, subject matter expert survey, and programmatic implementation. These approaches provided measure of the applicability and validity of the defined approach to leading indicator monitoring and risk identification. Ultimate validation will require prolonged study and more robust operational data management structures to allow for the temporal response modeling needed to assess the efficacy of identified producibility leading indicators.

5.4.1 Defect Rate Correlation

An extension of the previously presented retrospective review of product development program performance was conducted by examining quality nonconformance rates in conjunction with trial implementation of the producibility scoring system. Tenured subject matter experts in the manufacturing engineering discipline who were involved in early stages of development for the case study program were asked to retrospectively implement the assessment tool using original configurations of sample hardware. Concurrently, risk likelihoods were assigned defect rate ranges based on organizational quality standards. For each scoring outcome, factor weighting was defined using linear correlation with assigned aggregate risk likelihood values assigned based on observed defect rates in the sample hardware. By comparison of sample scoring trials, the Pearson correlation coefficient was maximized to arrive at weighting coefficients for aggregation of factor scoring that can support product development efforts. While the details of correlation are not shown for proprietary consideration, the resultant correlation was not statistically significant due to the limited scope of assessment trials. Additional scoring trials would support the statistical connection of defect rate ranges and the assigned likelihood based on organizational standards. The goal should be to support direct translation of aggregate leading indicator monitoring to risk management likelihood.

5.4.2 Subject Matter Expert Survey

Given the constraints of product development timelines on method validation, a survey was conducted of the tenured Manufacturing Engineering community within the supporting practicum organization to gauge applicability of identified leading indicators. Applicability of each indicator to observed producibility risk was interrogated on a five increment scale ranging from one for very insignificant to five for very significant. Again, the sample size was small (18 responses), but the average rating across indicators presented for assessment was approximately four corresponding to significant applicability to producibility risk. Figure 5-2 presents a sample distribution of ratings for the Capability factor group.

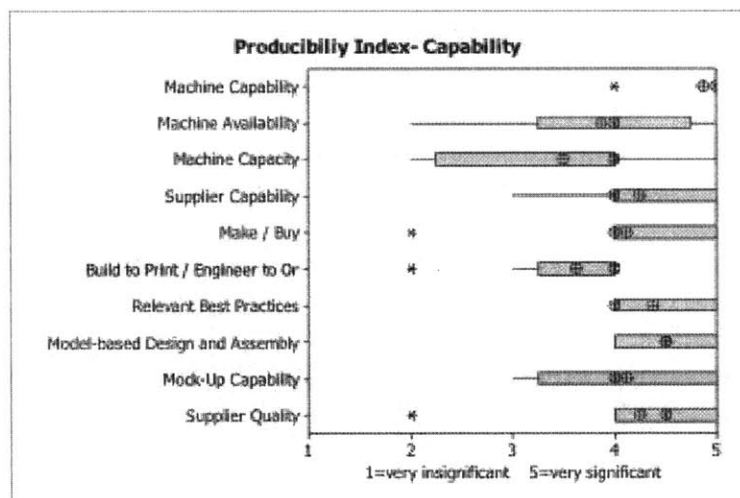


Figure 5-2: Example outcome of leading indicator assessment survey of Aerospace Corporation X Manufacturing Engineering discipline experts for applicability to producibility risk management

While statistical significance of this validation approach is again challenged by the sample size, it provides feedback from the constituents of the knowledge-based system that the extension of STPA methods does capture known sources of risk based on experience. Ultimately a more robust validation that does not incorporate hindsight bias of tenured experts should be conducted, but this initial validation supports continued development of the leading indicator framework and monitoring program.

5.4.3 Program Implementation

As a final measure of validation for the proposed methods, pilot implementation of the producibility risk indicator assessment framework was invoked on three concurrent product development efforts within Aerospace Corporation X. The development stage for all of the product development programs was preliminary design or earlier. Tool implementation as part of trade-studies was championed through Engineering and Operations management. Assessments were conducted within teams, either comprised of manufacturing engineers assigned to the programs or larger cross-functional teams inclusive of Operations technicians, design engineers, manufacturing engineers, and management.

Program specific findings and general organizational concerns resulting from the pilot team activities were assessed for producibility risk concepts beyond product configuration risk. Significant examples of program specific findings related to producibility were as follows:

- Process capability for transmission housings
- Ergonomics and obsolescence for electrical systems
- Supplier capability and validation methods for fuel systems

In addition, the following general areas of producibility governance insufficiency were highlighted by multiple teams:

- Early functional engagement / product team structure
- Supplier capability assessment and dissemination
- Manufacturing and tooling interfaces
- Extent of inspection and customer expectations
- Leadership incentives for performance
- Standard work alignment with existing business practices

While all approaches for validation of programmatic responses ended with non-statistically significant or qualitative results, the practicum organization expressed recognition of significant value in the proposed leading indicator framework. Risk was surfaced that both had significantly impacted prior or current product development efforts, and that is not addressed within current organizational risk management practice. Proposed activities to further explore the value and statistical significance of the framework are discussed in Chapter 6.

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Chapter 6

Conclusions and Recommendations for Continued Investigation

The case study of Aerospace Corporation X and the subsequent analysis of organizational control were presented to both explore the foundations of producibility risk in a complex aerospace product development environment and present a new approach to producibility risk management. As a result of these investigations, conclusions can be drawn on the efficacy of existing producibility risk management methods and opportunities for improved governance through leading indicator management. This section summarizes the findings within this investigation, touches upon the use of STPA-based methods versus other producibility management approaches, and suggests continued investigation to expand upon this work.

6.1 Origin of Producibility Risk

It was proposed for this investigation that producibility risk and resultant producibility shortfalls in aerospace product development efforts are primarily indicated by organizational design assumptions and associated phased implementation of programmatic control. Focus for this hypothesis was placed on the following four areas related to organizational design and control: development process isolation between functional and external groups, phased maturation of organizational capability, phased maturation of process control, and explicit

and implicit performance incentives. In addition, it was noted that dynamic nature of the organization with respect to the duration of aerospace product development must be considered when examining strategies for identification and management of producibility risk. The outlined considerations were explored with respect to the hypothesis on organizational government through two methods: (1) a case study of a large product development effort at Aerospace Corporation X and (2) an analytic extension of hazard analysis techniques from system safety to identify indicators of producibility risk. These assessments provide the basis for conclusions on the primary source of producibility risk in product development organizations as well as the basis for leading indicator identification to support improved methods of development risk management.

The case study was conducted using a recent, large-scale product development effort that incorporated new technology, new processes, and increased customer oversight for quality and performance. Incremental assessment of Aerospace Corporation X program performance attributes was conducted to interrogate the role of organizational processes and structure on producibility governance, as well as narrow the focus for subsequent system theoretic process analysis. Program schedules were noted to reflect an inflection point in performance between critical design and the build reflective of when producibility challenges become evident in the physical manifestation of the product. Configuration management focus on Design Engineering release schedules were observed to be ineffective in capturing the producibility challenges that affected the later phases of the program. Sourcing profiles from the case study product bill of material corroborated the industry trend of an extended operational structure involving outsourcing of most detail components and sub-assemblies, as well as increased information flows and interfaces. From the program management perspective, typical metrics of schedule and cost performance through the EVMS reflected producibility challenges consistent with organizational functional transitions, discrete review stages, and externalities. Conversely, risk management processes exhibited only a narrow functional focus and prioritization of product performance and schedule performance rather than producibility concerns. Finally, initial quality nonconformances highlighted many informational discrepancies in product definition that resulted in organizational rework cycles but no physical change to the product.

In aggregate, this review of product performance attributes for the case study program provided two important conclusions. First, it clarified that the assessment of producibility risk mechanisms should address a governance system inclusive of organizations, all functions, and outsourced component and sub-assembly fabrication. Second, the review highlighted that existing measures of program performance are not sufficient to capture sources of producibility losses. These measures however do identify organizational coordination and complexity in temporal information flow as challenges driving significant impacts to producibility.

Subsequently, a formal extension of system theoretic process analysis was proposed to identify inadequate organizational governance relationships for producibility along with associated causal mechanisms and forming assumptions. Three examples from an extensive organizational analysis were presented that covered intra-functional supervisory control within Operations for Product Quality and the Configuration Management Board, cross-functional control between the Product Centers and System Engineering, and management of external operations through Design Engineering oversight of Supplier Management. In each case, omissions and inadequacy in feedback control, along with flawed mental models of organizational processes, differing performance goals, and gaps in functional communication were identified. In addition, underlying assumptions dictating the activities for each controlling party were found to be constrained by functional perspectives rather than actual functional procedures.

With causation and assumptions understood, an aggregate assessment showed that out of all producibility control inadequacies, the majority of sources of producibility loss were a function of organizational control and temporal phasing of governance due to resource constraints. It, therefore, is concluded that the hypothesized sources of producibility risk, namely functional isolation, phased capability and control, and differing performance incentives are central to producibility loss within an organization. In addition, they are deemed to be more important than product feature-based sources of producibility risk based on their hierarchical, controlling relationship with product definition and influence on the process of physical manifestation of the product. While additional validation of these conclusions should be explored, monitoring of organizational indicators for producibility risk should be

a fundamental tenet of aerospace product development efforts.

6.2 STPA Extension to Producibility

Based upon findings from the trial extension of system-theoretic process analysis (STPA) methods for producibility, use of STPA is concluded to be valid and beneficial for identification of leading indicators of producibility risk. The STPA approach depicted in Figure 6-1 provides a systematic means to both assess and address the complexity of governance in the socio-technical systems of large aerospace product development organizations. In addition, it focuses on dynamic interaction between entities to understand information flows, control hierarchies, and discipline mental models that may not be consistent with standard work, procedures, and processes. In an analog to system safety, the temporal nature of governance and the opportunity for loss in the absence of explicit failures within the complex structure of the organization can be highlighted through the STPA extension. Most importantly, the STPA approach supports leading indicator identification and mitigation of producibility risk in product development efforts before the risk is anchored by product and process configuration. Implementation of the proposed methods will provide program management with a new approach to understanding and designing the product development organization, thereby ingraining governance needed to accommodate market and economic constraints on modern aerospace product development.

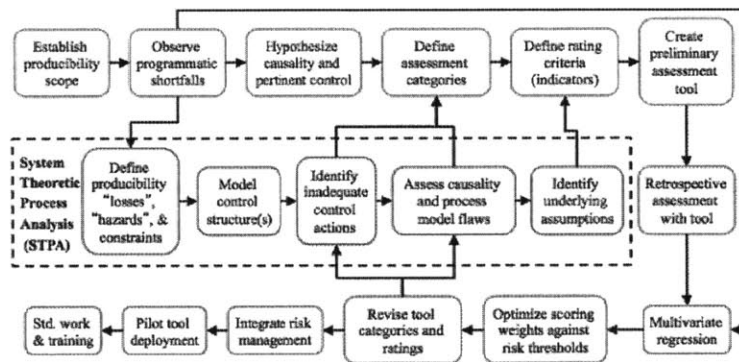


Figure 6-1: Method for identification of leading indicators of producibility risk using a system theoretic process analysis backbone.

6.3 Risk Management Incentive Hurdles

It has been concluded that assumptions in organizational design and governance are more pertinent to producibility risk than product attributes. In addition, it has been concluded that STPA provides a framework that allows for effective assessment and monitoring of producibility risk indicators in the product development organization. The value in these findings will be dependent on the ability of product development organizations to implement a robust leading indicator monitoring program in the presence of incentives counter to prolonged risk management. First, a true implementation of cross-functional risk management will be required to ensure all perspectives and tacit knowledge is integrated into the risk management process. Second, risk management processes and review must be independent of short term objectives associated with the stages of product development and often program management oversight. Finally, a culture of pro-active risk identification and mitigation will need to be established in organizations beyond Engineering. These characteristics are contrary to the siloed focus and execution incentives present within many aerospace producers with expansive operations, but are central to effective risk management programs. Open leadership valuation of the proposed risk management approaches and engagement of employees in risk management activities should be the first steps taken to overcome implicit incentive hurdles.

6.4 Continued Investigation

Value of the included analysis and proposed methods has been iterated, but more investigation is required to fully validate the approaches and facilitate integration into a variety of product development organizations. For this reason, it is suggested that focus of future efforts be first placed on defining an operational data structure necessary for validation of the STPA extension for leading indicator identification. This should be complemented by additional and broader retrospective assessments of product development efforts to understand the level of correlation between indicators and outcomes. With these validating activities completed, decision theoretic approaches and indicator forecasting should then be examined to allow for

new frameworks that leverage identified risk indicators in organizational decision-making. The goal is to not only have a comprehensive STPA-based approach to producibility risk management, but to allow for complete and efficient mitigation of producibility risk early in product development.

Appendix A

Producibility Control Structures

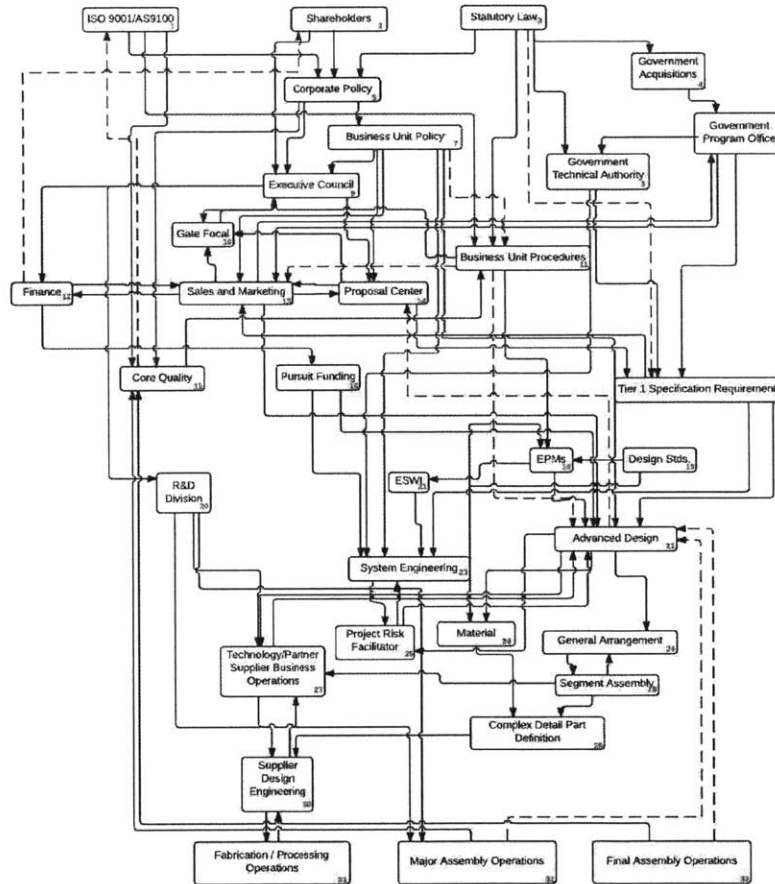


Figure A-1: Producibility control structure for the Concept Development and Business Acquisition phases of development at Aerospace Corporation X

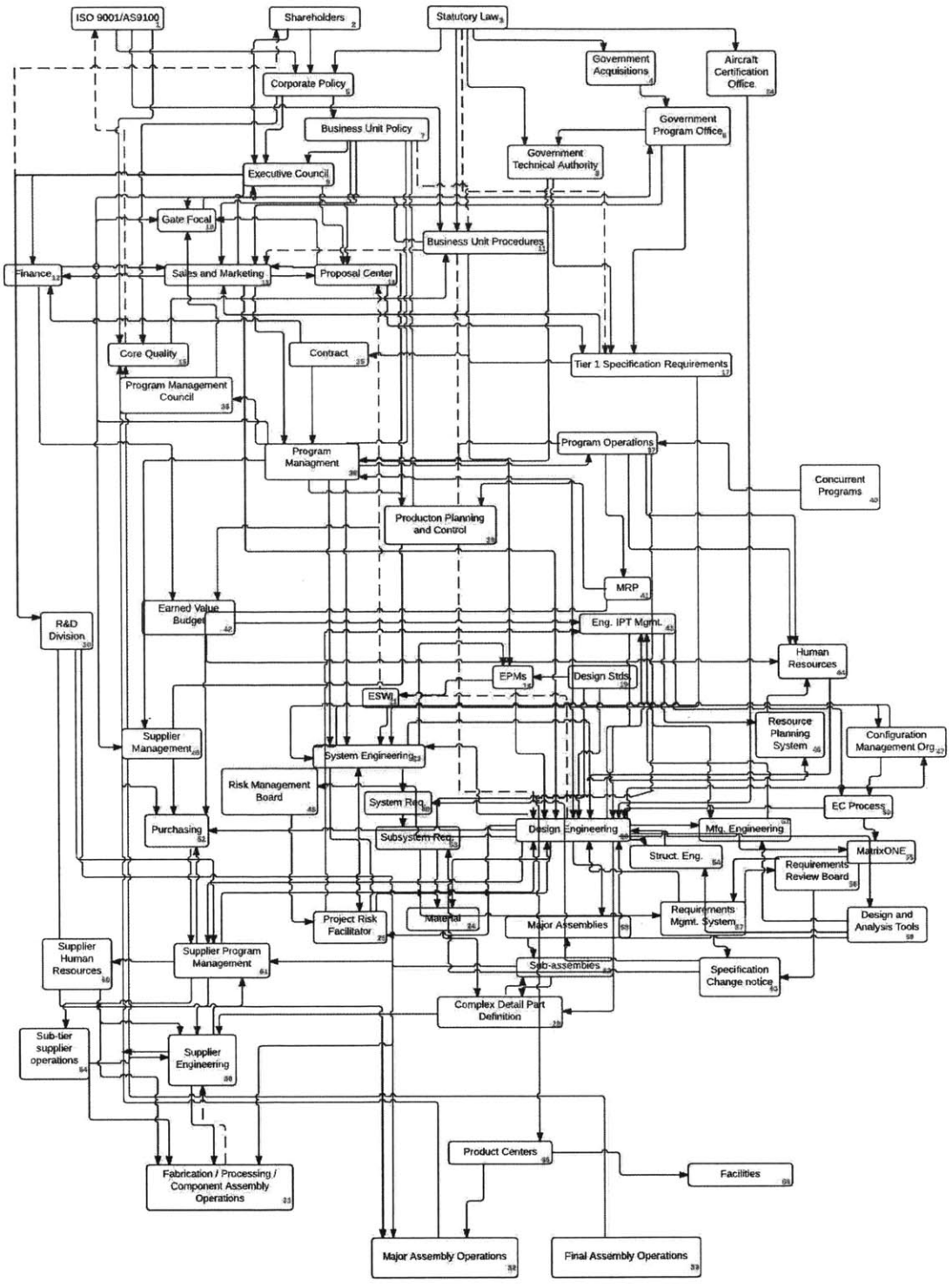


Figure A-2: Producibility control structure for the Preliminary Design and Detailed Design phases of development at Aerospace Corporation X

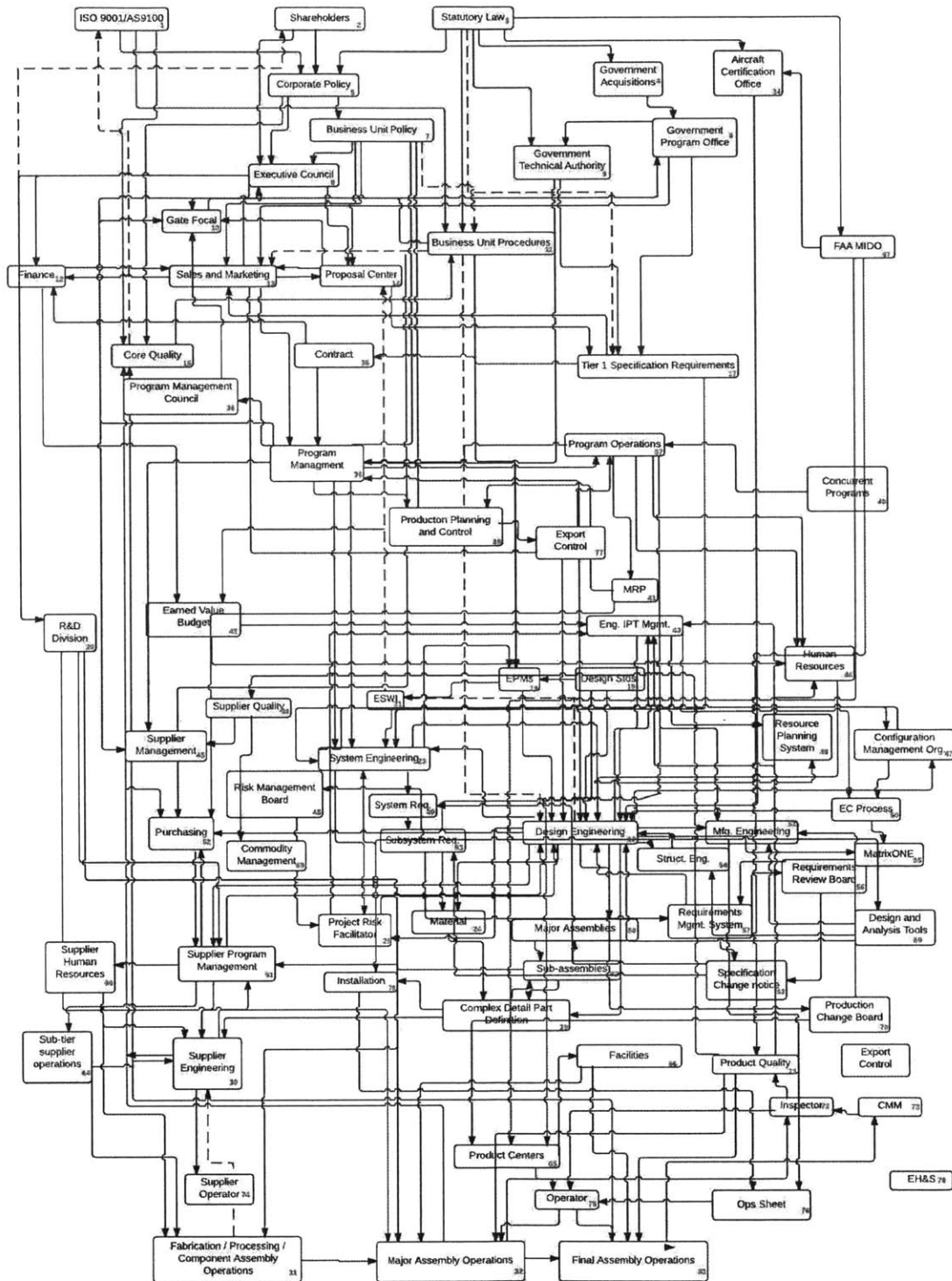


Figure A-3: Producibility control structure for the Production Engineering and Initial Build phases of development at Aerospace Corporation X

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Appendix B

Organizational Interface Mapping

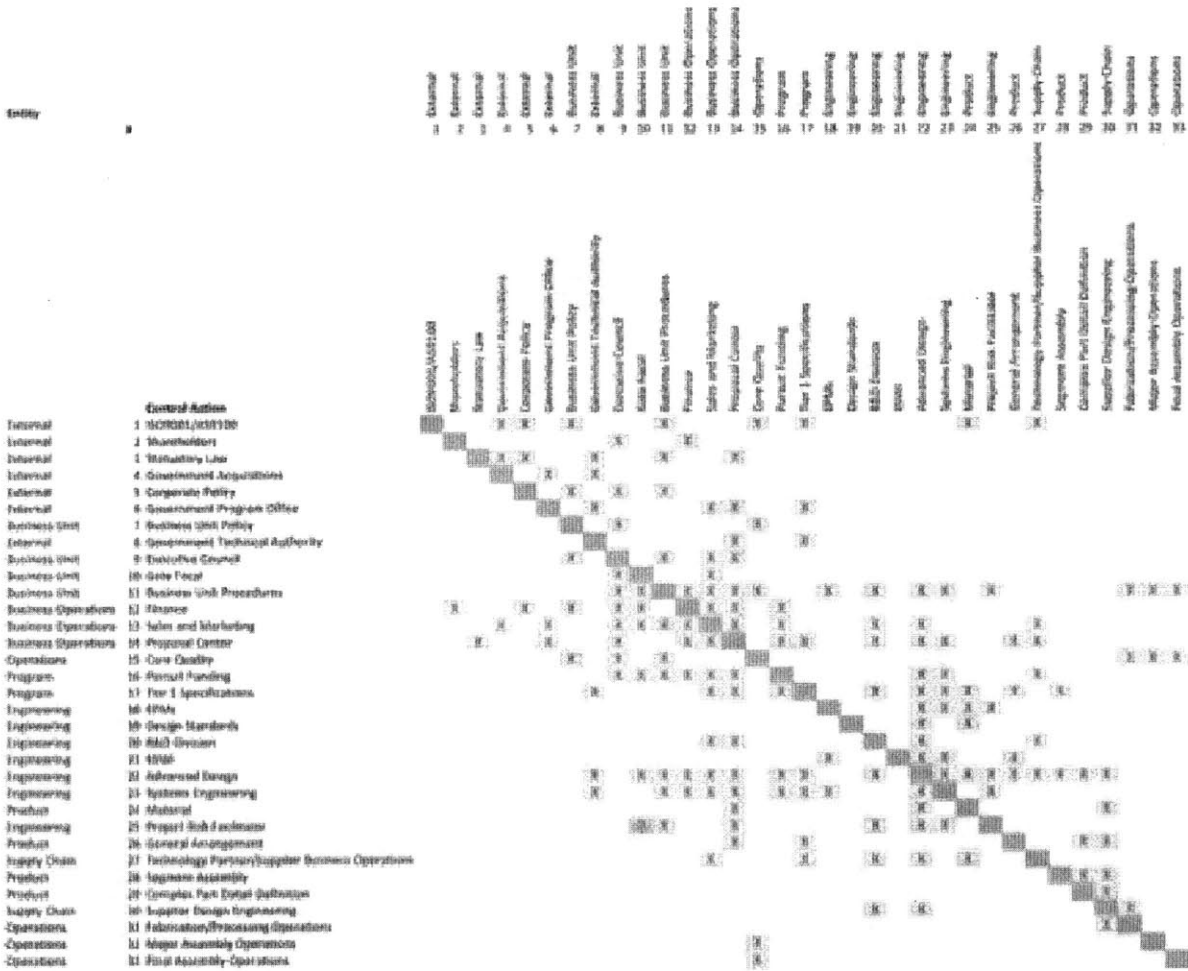


Figure B-1: Design structure matrix for identification of producibility control interfaces in the concept development and business acquisition phases of product development

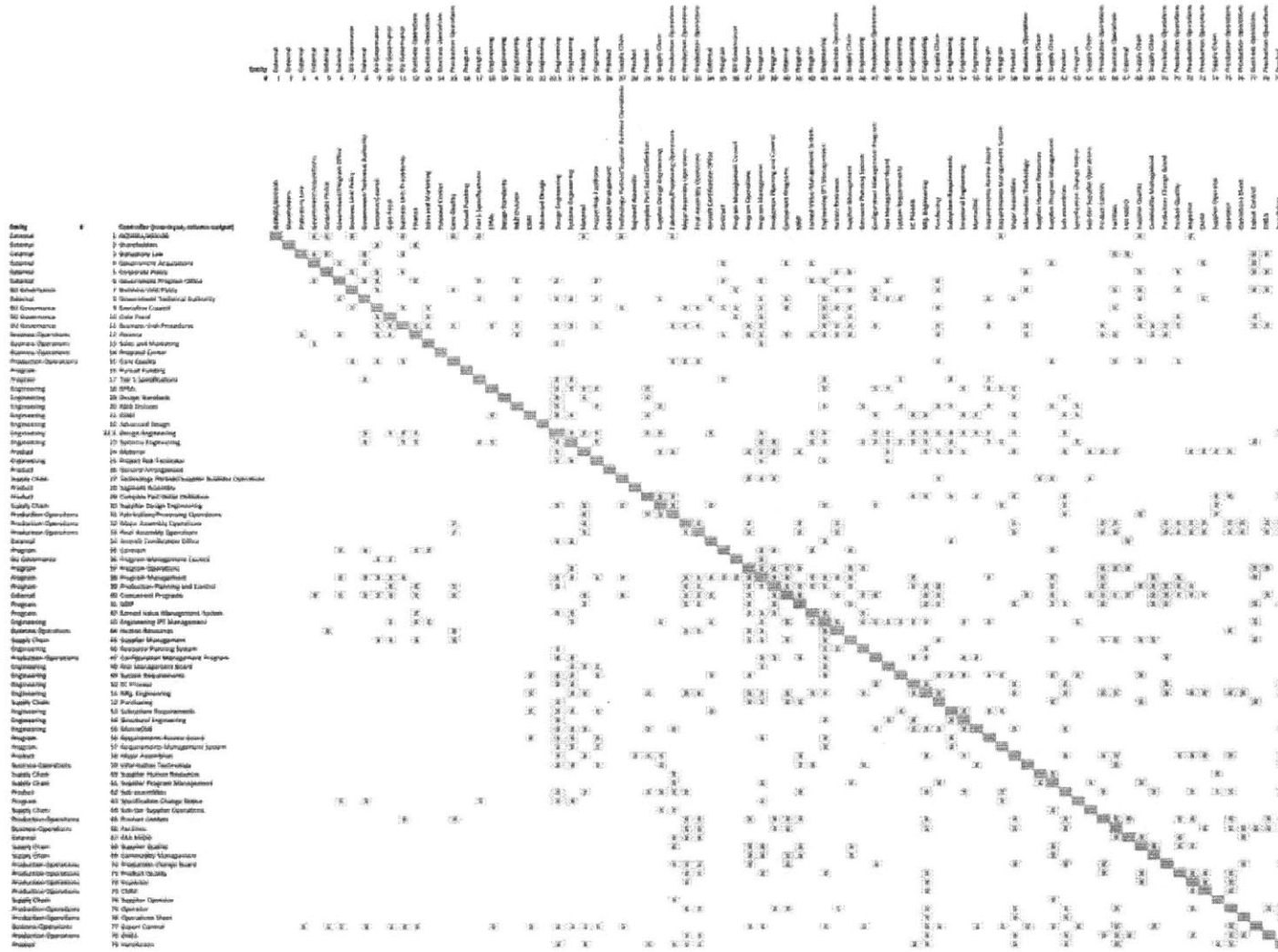


Figure B-3: Design structure matrix for identification of producibility control interfaces in the production engineering and initial build phases of product development

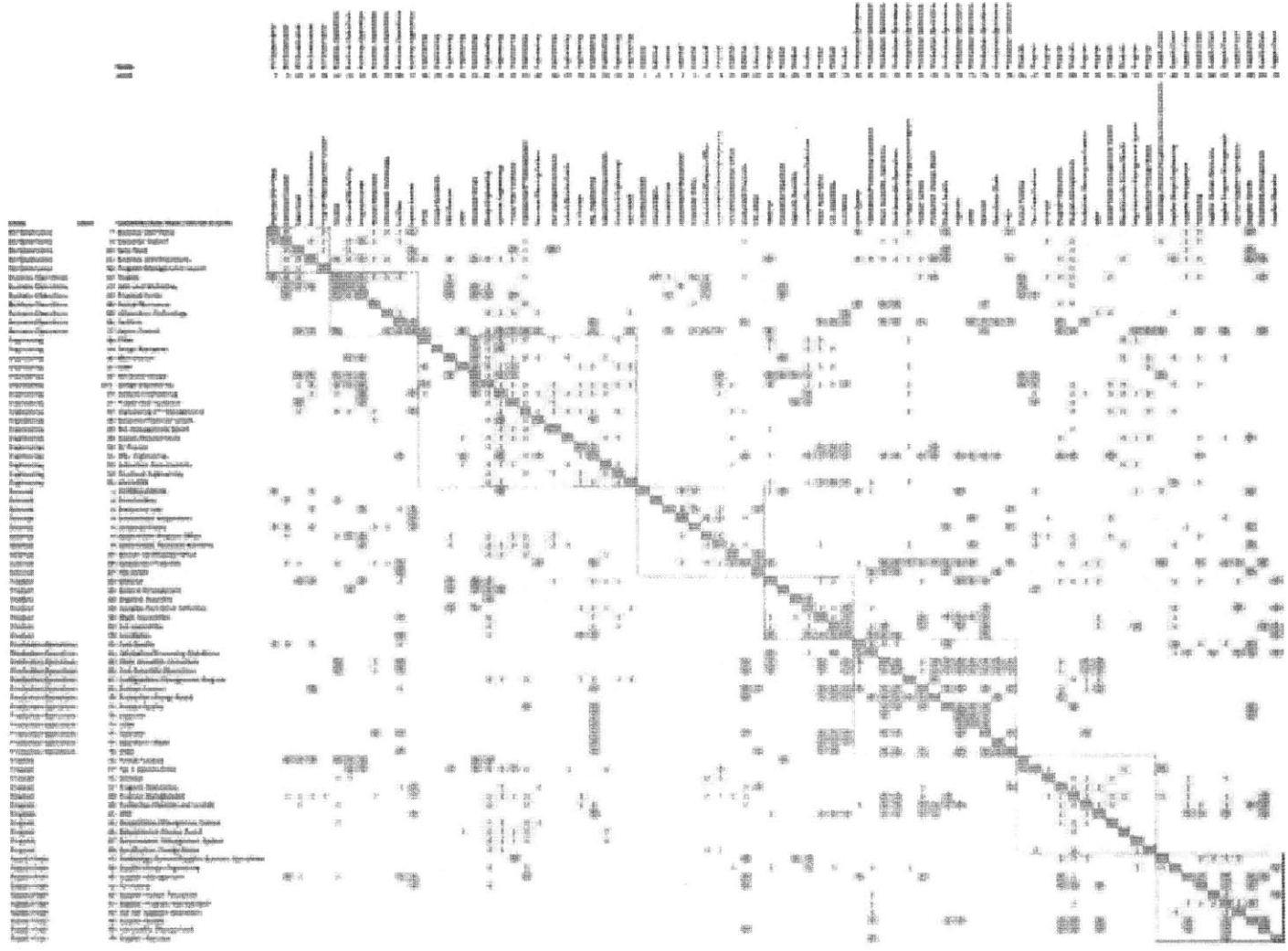


Figure B-4: Overlap design structure matrix for identification of producibility control phasing and omissions in the product development cycle

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