

**Application of Variation Risk Management Processes in Commercial Aircraft  
Design and Manufacture**

by

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Bachelor of Science in Mechanical Engineering, Massachusetts Institute of Technology  
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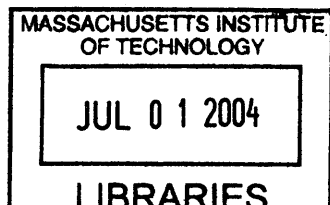
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**BARKER**

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Submitted to the Department of Mechanical Engineering and the Sloan School of Management on May 14, 2004 in partial fulfillment of the Requirements for the Degrees of Master of Science in Mechanical Engineering and Master of Business Administration

## **Abstract**

Companies and academics have known for many years that reducing variation in production processes can decrease production cost, increase product quality, and have substantial impact on overall profitability. Tools to help companies track, assess, and improve variation are numerous and readily available, but gradually an understanding has emerged from implementing these tools that significant amounts of variation cannot be removed from the factory, and the only way to continue to improve cost and quality beyond diminishing returns is to move upstream in the process and design parts and assemblies that are more variation resistant, or maintain quality functionality over a broader range of variation. One methodology emerging to help companies with this task is Variation Risk Management (VRM).

The problem with VRM and other methodologies is that they are often treated as side processes that do not get well integrated into the overall product development process. This results in training and improvement activities that optimize VRM on its own rather than maximizing the effect VRM has on the product. In order to do this the initiative failure cycle must be understood, and attention must be focused on information management, management and organizational support, and process like communication and integration.

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## **Chapter 1: Introduction**

Companies and academics have known for many years that reducing variation in production processes can decrease production cost, increase product quality, and have substantial impact on overall profitability. Tools to help companies track, assess, and improve variation are numerous and readily available, but gradually an understanding has emerged from implementing these tools that significant amounts of variation cannot be removed from the factory, and the only way to continue to improve cost and quality beyond diminishing returns is to move upstream in the process and design parts and assemblies that are more variation resistant, or maintain quality functionality over a broader range of variation. One methodology emerging to help companies with this task is Variation Risk Management (VRM).

This thesis explores VRM, including an in depth analysis conducted at The Boeing Company, and draws out themes, processes, and practices that can be universally applied across industries and companies.

This chapter gives the context of the thesis work, including an introduction to The Boeing Company and VRM terminology and tenets. Additionally, the problem, project, and hypothesis are introduced.

### **1.1 Boeing Overview**

Founded in 1916, Boeing has grown into a multinational corporation best known for building large commercial jetliners. Its 166,800 employees are broken into five major units: commercial airplanes, air traffic management, Connexion by Boeing (in flight broadband), Boeing Capital, and Integrated Defense Systems. These units combined in 2003 for \$50.5 billion in profit (Boeing 2003).

The Boeing Commercial Airplanes (BCA) division is currently embarking on the design of a new 200-250 seat jetliner designated the 7E7 Dreamliner, scheduled for first delivery in 2008. This aircraft is being designed as a light and fuel-efficient alternative to other planes in this market, and will employ composite technologies to an extent never before attempted on commercial jetliners. Major objectives for this aircraft relevant to this thesis are:

- Approximately 80% reduction in final assembly time from current products (Puget Sound Business Journal 2003)
- Large but undisclosed reduction in manufacturing cost
- Improved quality over existing products

VRM is one methodology by which BCA hopes to achieve these and other goals.

## **1.2 Variation Risk Management Overview and Definitions**

Variation Risk Management is defined as the holistic view of variation concerned with the proper allocation of limited resources to identify, assess, and mitigate variation in order to improve quality and reduce cost as efficiently and effectively as possible (Thornton 2003). For simplicity in understanding the breadth and limits of this definition, it is important to understand that VRM can be seen as the unification of Variation Management (VM), and Dimensional Management (DM).

Variation Management is typically done in the factory during production. It can be defined as the systematic allocation, based on cost and risk, of limited resources to either reduce variation or reduce the impact of variation (Thornton 2003). Rather than attempting to replace such methodologies as Six Sigma or Statistical Process Control (SPC), this part of VRM is more concerned with laying out a framework to target and prioritize variation reduction efforts to gain the most benefit from company resources (i.e. Six Sigma blackbelts).

Dimensional Management can be viewed as designing products with the effects of variation in mind. Thornton defines DM as the tools used to manage and design for the variation in individual dimensions. These can include GD&T (Geometric Dimensioning and Tolerancing), datum schemes, and measurement methods (2003). By understanding the interface points and interactions between parts, “key characteristics” can be identified that drive product quality and performance. By analyzing and understanding these key characteristics (KCs), targeted efforts can be undertaken to reduce the variation, increase the design’s robustness – or resistance to variation – or redesign for improved qualities in an efficient and data-driven manner.

VRM ties these two parts together in a continual loop. By identifying KCs during the design phase, production can better target VM analysis and improvement efforts for maximum effect. The data collected by production on capability and quality issues can then be fed back to development to better identify and analyze KCs, and thus design for the capabilities of production. The more cycles a company follows VRM processes through, the more focused and less costly its VRM efforts can become.

Useful definitions for understanding VRM are as follows:

**Table 1: Variation risk management definitions**

Definitions	Term	Definition
	Key Characteristic (KC)	A feature of a system, assembly, part, or process, whose expected variation from nominal has an unacceptable impact on cost, performance, or safety.
	Dimensional Management (DM)	The tools used to manage and design for the variation in individual dimensions. These can include GD&T (Geometric Dimensioning and Tolerancing), datum schemes, and measurement methods.
	Variation Management (VM)	The systematic allocation, based on cost and risk, of limited resources to either reduce variation or reduce the impact of variation.
	Variation Risk Management (VRM)	The holistic view of variation concerned with proper allocation of limited resources to identify, assess, and mitigate variation in order to improve quality and reduce cost as efficiently and effectively as possible.

VRM will be discussed in greater detail in the chapter 2.2, but these initial definitions were deemed helpful as a brief introduction to the problem statement.

### **1.3 Problem Statement and Hypothesis**

The Airplane and Services Integration Team (ASIT) has responsibility for developing and managing a VRM plan for the 7E7 Dreamliner development. They have their own ideas on how to accomplish this task, based on their collective experience with past airplane programs. The team has decided, however, that an independent review and validation of processes and tools should be conducted before committing to a potentially flawed course of action.

The problem is that Boeing has identified variation management and proper allocation of tolerances as critical to the 7E7 program success, but needs actionable enablers for the success of these activities given the timeline and resource constraints of the program and the company.

The Boeing-specific hypothesis is that VRM activities and personnel are constrained by more than VRM-specific tools and processes, and the most effective methods for enabling VRM success will require action from upper management rather than the ASIT team themselves. A more globally applicable hypothesis is that processes and tools enable VRM success, but information, organization, and management structure are the main factors determining the degree of success a VRM program will experience.

### **1.4 Project Description**

This project served as an independent review of the 7E7 Dreamliner Variation Risk Management plan. Daily work was conducted as a member of both the ASIT team and the Final Assembly and Delivery (FAD) team, whose primary responsibility was

determining how pieces of the aircraft would be delivered to Boeing, assembled, tested, and made ready for delivery to the customer.

Access to previous VRM practitioners and existing commercial product final assembly areas was available, as was access to current VRM tools and process documentation.

The project had a duration of six months, at the end of which recommendations were made along with supporting evidence from variation analysis projects conducted using principles discovered during the project.

### **1.5 Organization of Thesis**

The layout of the thesis is as follows:

Chapter 2 introduces the history of Variation Risk Management within Boeing as well as discussing themes in literature and academia both directly and indirectly pertaining to VRM.

Chapter 3 focuses on the methods employed to attack the problem and validate the hypothesis.

Chapter 4 describes the cargo floor case study. After a situational overview, the process steps and tools will be described, along with the method of communicating the results. Additionally, the success of the project will be discussed from an effectiveness standpoint.

Chapter 5 puts a brief framework around the next three chapters.

Chapter 6 describes how Requirements, Key Characteristics, and Process Capability are critical to developing cost effective parts that assemble with robust quality.

Chapter 7 discusses the appropriate metrics, proper assignment of accountability through those metrics, and appropriate team structure for VRM. The cycle of initiatives, or the tendency for initiatives to replace initiatives - only to get replaced by yet another initiative, is also discussed.

Chapter 8 discusses the tendency to sub-optimize small pieces such as data collection, VRM, and engineering rather than optimizing the entire processes of product development, and focuses on three of the biggest returns on investment: improving the data collection process, the communication process, and the integration process.

Chapter 9 aims not to summarize the information contained in this thesis, but to synthesize the various case studies, lessons, and ideas to present a final look at VRM from a development process perspective. The hypothesis will be discussed to determine if there was enough data to support it, and some final thoughts on how to best improve an organization's VRM program will be considered.



## **Chapter 2: Background and History**

This chapter introduces the history of Variation Risk Management within Boeing as well as discussing themes in literature and academia both directly and indirectly pertaining to VRM. Additionally it contains a brief discussion on how these themes pertain to the previously stated hypothesis.

### **2.1 VRM History within Boeing**

Boeing has conducted variation risk management initiatives for more than two decades. During this time, concepts that currently fall under the moniker of VRM have gone by several different names. Often the same concept or process was “reborn” under a new name either to shed the assumptions and controversy associated with the old name, or because the tools themselves changed names or brands.

Adding to the complexity is the fact that the initiatives were introduced to different geographies at different times, and on occasion, under different names. For simplicity, this section will briefly focus on a single thread of this history for Commercial Aircraft in Puget Sound. Many related initiatives, such as quality circles, are left out.

People recall the identification of Key Characteristics back into the ‘70s. At the time the term was confined to using statistical processes to look at deviation and its effects, but the idea of focusing in on specific dimensions with the greatest effect on quality began to spread. While this idea grew, the next significant step in the evolution appears to be in the late ‘80s, when D1-9000 came into existence.

The D1-9000 document was initially a list of requirements levied on BCA suppliers, centered on identifying and measuring KCs. The document was owned by procurement and quality assurance, and served as a reference to vendor managers who wanted to discover the maturity of their vendors’ design practices. D1-9000 focused on variation

management through statistical process control (SPC) more than dimensional management, but clearly had aspects of both.

As the document grew and matured, multiple internal groups began qualifying themselves to the standard. With the increased use the need for more structure became apparent. The D1-9000 contained sections entitled AQS (Advanced Quality System), and as these sections expanded in use and breadth, a full blown initiative termed AQS was launched.

AQS still maintained the document numbered D1-9000 as its reference document, but began to put some focus on dimensional management as well as variation management. At this point it is useful to talk about content at a high level. Designed as a document to validate or help control production, AQS focuses on laying out requirements, listing ways to validate requirements are being met, and presenting flowchart processes and their associated tools for validation or troubleshooting. Even the most updated version of the document does not go much beyond laying out a framework manufacturers are expected to follow or conduct business within (Boeing Company, 1996a).

At some point a small group of AQS experts who felt AQS was not focusing on the proper tools or processes created the Hardware Variability Control (HVC) program. HVC and AQS maintained separate but overlapping domains, related loosely through their common use of key characteristics. With the weight of the 777 strategic initiative, HVC gained traction quickly. A steering committee was set up to help manage the effort, and training began in earnest to teach people about the processes and tools of HVC.

Eventually AQS and HVC were joined in November 1996 via the D1-9011 linkage document. This document merged the HVC and AQS processes with the understanding HVC was contributing the majority of DM activities and AQS the majority of VM activities under a continuous “Plan-Do-Check-Act” process (Boeing Company, 1996b).

After learning from the 777 development program, HVC focus shifted slightly for the 737 Next Generation program but still maintained its structure. Soon after the 737NG program ended, however, HVC lost speed, focus, and some credibility with production personnel, and the initiative eventually ceased to be. Many hypotheses exist as to the reason for the program's end, but the most likely were the high costs of the HVC committees and activities, the lack of clear representation of cost savings HVC brought about, and the factories' disillusionment with the measurement programs HVC created.

One steering committee member said, "We turned off the community of SPC with HVC, so we needed a new name to get going with this again." Six-sigma was gaining in popularity for VM tasks, and so many HVC alumni refocused on six-sigma, using many tools already familiar to HVC. The six-sigma group in BCA has been recently dismantled.

DM tasks and tools have stayed with the company under different names. While in actuality they are distinct processes and technologies, Determinate Assembly (DA) and Advanced Technology Assembly (ATA) are often used as interchangeable terms for Dimensional Management.

The current situation BCA finds itself in seems to be a fragmented one, where some people focus on variation management and some focus on portions of dimensional management. There is a great deal of focus on DM and VM tools, but very few people focus on the processes of DM or VM, and fewer on the overarching process to effectively combine the two processes to maximize the benefit.

Other details of the current situation must be understood and appreciated before a path for the future can be discussed. Important topics are attitudes toward initiatives, key characteristics, taking production measurements, and career advancement.

### **2.1.1 Initiatives**

VRM practitioners in BCA have lived through name changes, tool changes, focus changes, and leadership changes within the last few years. This refers only to VRM initiatives, and does not take into account any other changing corporate initiatives these VRM practitioners have undertaken. Each of these initiatives or changes was likely the right thing to do at the time, but the more things change, the more the people will stay the same, either ignoring or paying mere lip service to the current directive. This situation is called the “flavor of the month problem” in other companies. In order to get buy in for new VRM tasks and processes, this situation must be understood and accounted for.

### **2.1.2 Key Characteristics**

KCs have been a part of Boeing for nearly 30 years. Over that span the answer to the question “what is a key characteristic” has changed multiple times. This gives rise to two very real problems. The first is that people who have had bad experiences with KCs will be resistant to anything termed “KC” in the future, even if it is a genuinely new and/or useful concept. The second problem is that people who know an old definition for KC may intentionally or unintentionally ignore a new definition for the term, and in turn cause confusion on future projects.

Industry, in the mean time, has mostly standardized on the term “key characteristic.” Boeing must now decide between using industry standard terminology, which may require a full-scale reeducation effort, and using non-industry standard terminology, which may confuse partners or suppliers who use the industry standard terms. Both efforts are similar, but it will be more difficult to determine the effectiveness of the reeducation effort since simple use of correct terminology will not be an indication of proper knowledge.

### **2.1.3 Production Measurements**

Every interview conducted within Boeing spent significant time discussing measurements in the factory on key and non-key dimensions. Engineering, operations, and quality all

accepted the fact that 777, and to a lesser degree 737 NG, required unnecessary measurements to be taken during production. These measurements required significant time, effort, and money to take and record, and the benefit was never shown or adequately explained to those tasked with taking the measurements. In 1997 the lack of explanation for expensive measurements came to a boil with Mitsubishi Heavy Industries and Kawasaki Heavy Industries, among others. Animosity and mistrust still exists within Boeing and within the supply base from this experience, and any plan that involves the taking of extra measurements will need to deal with this sentiment.

#### **2.1.4 Career Advancement**

Interviews shed light on the fact that VRM was initially seen as a path to career advancement for many people. Because it was a relatively new specialization there were very few experts in the company, and the potential for rapid advancement enticed many to specialize in VRM tools or processes. As a counterpoint, more than one person encountered within the company did not readily admit they were very experienced with HVC because they felt association with that initiative was now a career hindrance. In order to make future VRM programs successful people must feel confident the skills they learn will be appreciated and rewarded. Without that incentive to learn, VRM will likely be a “flavor of the month.”

#### **2.2 VRM Research and Uses**

The history leading up to today’s thinking in VRM and variation analysis is too broad to effectively discuss, so this chapter will better define the distinct aspects of VRM as well discuss some advanced research in these areas. The framework used for discussion will be Thornton’s three phases of VRM: Identification, Assessment, and Mitigation, shown in Figure 1, adapted from the same text (2003). Not all aspects of this methodology will be discussed or defined, and those seeking better definition than contained in this thesis should be directed to said text.

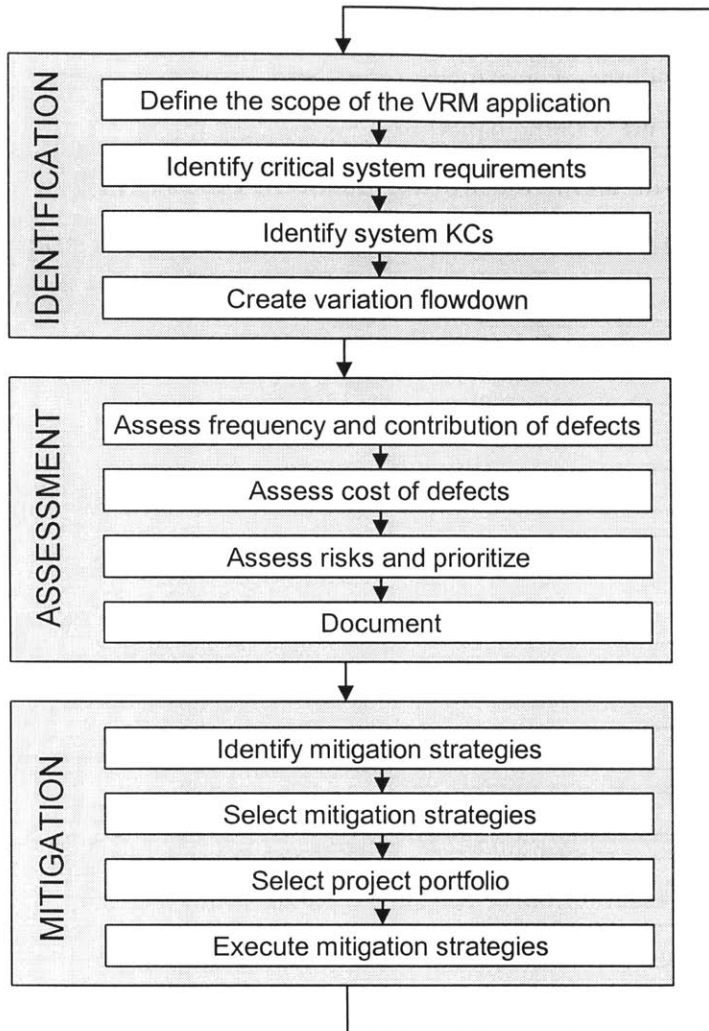


Figure 1: VRM Methodology

### 2.2.1 Identification

While defining the scope of any project is critical, for this discussion the identification phase will begin with requirements and end with a variation flowdown, which defines the key characteristics and their interactions via part features and processes to define “variation chains” that contribute to the performance of the product relative to the requirements.

Variation risk management begins with the identification and subsequent ranking of requirements, whether corporate, regulatory, or customer. VRM does not necessitate any

particular methodology for this task, and many practitioners use methodologies such as Quality Function Deployment, which focuses on taking the “voice of the customer” and determining and ranking product requirements (Mazur 1996). Countless other methodologies exist for this function, and can be researched easily.

Initial KC identification and the subsequent flowdown creation can be either “top-down” or “bottom-up.” In bottom-up analysis, individual parts are assessed and critical dimensions for performance determined. The engineer puts the analyzed piece parts either physically or virtually into their assembly and determines the next level of critical dimensions in order to meet the top-level requirements. Top down analysis starts with the critical product requirements and determines which aspects of the assembly or assemblies are most critical to meeting that requirement. When that is determined, the part or sub-assembly is analyzed to determine what aspect is most critical in meeting the higher-level performance requirements.

These two methods of flowdown creation are not mutually exclusive, and usually companies will practice both to a certain degree, though it may heavily favor one method over the other. Reasons to favor bottom-up include a desire to reuse existing parts for time and cost savings as well as its relative ease when compared with the top-down process. The top-down process, however, is generally assumed to have favorable results for the product, though its time and monetary costs must be considered as well (Whitney 2004).

The speed of the particular development cycle will drive the number of times the developers cycle through the identify, assess, mitigate loop, so it is important to note now that an initial variation flowdown on a new product may have little or no supporting data at this point, whereas an update to an existing product may have a great deal of data associated with the flowdown structure on the first cycle.

### **2.2.2 Assessment**

Any way a company chooses to create the flowdown, it has three main methods of assessment: educated guesses, measurements either on test pieces or similar production pieces, or simulation (Craig 1995). Within these three categories there has been a great deal of research on methods to aid in analysis. A brief overview of the tools, or model types, available is listed in table 2 below (Thornton 2003).

**Table 2: Model types, inputs, and limitations**

Prediction Tool	Model	Input Data	Limitations	Accuracy	Time to build (complexity)
Previous designs	Performance of previous design	Previous designs	Based on engineering judgment	Fair	Low
Qualitative	Performance of previous design	Engineering judgment	Not based on numbers	Fair	Low
Extreme value analysis	Performance model	Process capability	Gives the worst case, but simple to analyze	Fair	Med
Tolerance validation	Tolerance model	Engineering tolerances  Process capability	Dependent on correct allocation of tolerances and availability of accurate process capability data	Fair	Low
Root-sum-squared	Sensitivity model	Process capability	Can be time consuming to build sensitivity model	Good	Med-High
Monte Carlo	Performance model	Process capability	Time consuming to run the model	Excellent	High
Geometry-based variation simulation software	Assembly model	Process capability	Useful only for geometry <sup>1</sup>	Excellent	High
Statistical correlation	Statistical model	Previous designs	Shows only correlations, not causality	Excellent	High
Prototype	Prototypes	N/A	Only as good as prototype	Good-excellent	High

<sup>1</sup> This statement is difficult to understand, since all the models listed are truly only useful on geometries of parts and assemblies. However, it is likely Thornton means that it is only useful for the actual geometries of the parts in the CAD system, and abstractions or partial-geometry investigations may not be possible without the additional task of creating entirely new analysis-specific geometries.



Research in the medium to high complexity models has been extensive. Even the relatively straightforward root-sum-squared (RSS) method has papers discussing the theories (Scholz 1994) and effectiveness in case studies (Altschul and Scholz 1994). While relatively easy to comprehend and learn, RSS capability in analyzing linear geometries is far reaching.

Monte Carlo analysis goes a step beyond RSS and provides a statistical analysis of final build tolerances under a wide range of different designs and component tolerances that were defined by the analysis (Excell 2003). Monte Carlo analysis is often used by geometry-based variation simulation software to analyze variation, and is often completely embedded in the CAD system, which allows existing CAD users a quicker learning curve due to their familiarity with the user interface (Schmidt 2000).

Despite the success of commercially available methods, much research is done on advanced methods of analysis. There is no shortage of work investigating new applications for analysis (Soderber and Lindkvist 2002) or new approaches (Srikanth et al 2001). Most agree that the purpose of tolerance design in product components is to produce a product with the least manufacturing cost possible, while meeting all functional requirements of the product (Lin and Chang 2002), but each promotes their method as the one that will save more money.

No research was found which analyzed what types of problems or situations were best analyzed by which method, and few comments were uncovered in research documentation discussing when not to use the suggested analysis. Each article merely dove into the technical merits of the analysis and presented the facts to support the method's validity.

### **2.2.3 Mitigation**

Determining the proper mitigation strategy is crucial to a cost-effective VRM exercise. The “correct” strategy depends a great deal on where in the development cycle the product is, what a company’s production system is capable of, and business strategy. Generally, a company can mitigate based on design changes, process changes, process improvements, monitoring, or inspection (Thornton 2003). Each of these options is a field of study unto themselves, but design changes and process changes will be discussed briefly.

Generally it is easier to mitigate via design changes early in the product development process. Once a product is in production, it may be costly or difficult to phase-in new parts or assembly methods. If the cost is not prohibitive, creating new designs is an option, via whatever methods the engineering department is comfortable with. Tooling can be redesigned to deliver the product quality desired, or lastly a company may chose to mitigate risk by validating or qualifying the product on an existing production line.

Mitigation based on changes to the production can also be costly and difficult, depending on the situation the company is in. If a new production line is being built for the product, changing the processes to achieve higher quality and tighter tolerances can be looked at as an incremental fee above the baseline process, and may be easier to justify the cost. Swapping processes on an existing line can have far reaching impact and cost that may uncover roadblocks such as space constraints, lack of experienced workers on the new process, or union issues.

### **2.3 History’s Role in the Hypothesis**

Documentation and research into VRM tools is plentiful. Sources for VRM processes are less abundant, but enough exists to give any company a viable roadmap. Why then, is it so difficult to find a company with a thriving VRM practice?

Boeing has used variation risk management processes and tools for well over a decade in all areas of BCA, yet finds itself in the position of starting the VRM effort on the 7E7

with only a handful of practiced experts. Despite having some of the most cutting edge tools for tolerance analysis and a mandate to use them, the magnitude of VRM influence on the designs is minimal (This is especially dangerous due to the unforgiving nature of composites when compared to traditional aluminum).

If access to the latest processes and tools, plus a core of people knowledgeable in how to maximize the effect of them is not enough to predict the effectiveness of a VRM effort, what else is required? Only one article (Thornton et al 2000) could be found that addressed companies' desires to reduce variation while discussing their struggle in executing on these strategies.

This realization, along with interviews, case studies, and analysis led to the hypothesis that processes and tools enable VRM success, but information, organization, and management structure are the main factors determining the degree of success a VRM program will experience.

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## **Chapter 3: Thesis Methodology**

This chapter focuses on the methods employed to generate actionable enablers for VRM success at Boeing and validate the hypothesis that information, organization, and management structure are the main factors in determining the degree of success a VRM program will experience. The overall process involved creating a whitepaper, validating the findings included in the whitepaper on an actual variation issue facing the team (a “case study”), and then closing the loops by updating the whitepaper with the findings and communicating all pertinent information throughout affected teams within BCA.

Chapters 4 through 8 explain in full the work described in this section.

### **3.1 Create a Whitepaper**

The 7E7 team felt the best medium for the independent review and the most rapidly deployable to all effected groups would be a whitepaper. As defined by [hyperdictionary.com](http://hyperdictionary.com), a whitepaper is a document whose purpose is to educate. The whitepaper was chosen to both heighten awareness that the author had no political incentive for writing the document, and to focus reader’s attentions on the issues to be considered more than the possible solutions presented. Agreement amongst all interested parties would be ideal, but initiating a dialogue about VRM and VRM issues was the minimum definition of a successful paper.

Based on the past experiences and present situation of VRM at Boeing, it was a goal of this whitepaper to draw out and present best practices applicable given the current state of knowledge throughout BCA. This current view would then be compared to the 7E7 VRM plan to determine any beneficial changes that need to be made.

The general process for this white paper was to ask similar questions to as many people with VRM experience as possible, and then extract from that data a list of common knowledge, best practices, and unique solutions.

The analysis process began with a list of questions created by the author (Appendix 2). The questions were generated from researching Variation Risk Management books, periodicals, and Boeing documentation. The questions were structured to achieve several objectives. The key objectives are listed in Table 3 below.

**Table 3: Interview Objectives**

Objectives	Goal During the Interview	Overall Goal
	Determine the extent of the individual's knowledge	Determine the current state of VRM knowledge within Boeing
	Discover tools, documentation, and processes available during projects	Determine Boeing's process capability and ability to make necessary tools available to everyone.
		In conjunction with above goal, determine Boeing's training effectiveness.
	Extract opinions and data to support opinions on effectiveness of processes and tools	Build a list of perceived best and worst practices
	Examine management practices during projects	Determine Boeing's ability to manage, track, and quantify VRM processes

An effort was made to make data collected comparable from interview to interview. However, if rich information was found in a particular area of expertise, that information was pursued. Therefore each interviewee may not have been asked each question directly.

After all interviews were completed, some interviewees were contacted again to fill in information holes or validate writings and assumptions.

The interviewees were initially selected from a short list of current dimensional management experts. Each interviewee was asked to provide names of additional experts, people with limited experience, and people who had a poor experience with the

topic. The list of interviewees expanded in this manner until three weeks before the whitepaper completion date. Fifteen interviewees were deemed internal VRM “experts,” four interviewees had limited experience with VRM training or factory measurements, and the other interviewees either had average experience levels with VRM or deep expertise with some aspect of VRM, such as statistics or tolerance modeling. Though to some respect all the interviewees had one or many “poor experiences” with VRM, only one interviewee knew of an individual who vocally despised all aspects of VRM, and unfortunately that person failed to respond to multiple requests for meetings or information.

The whitepaper and the results of the interviews are the basis of Chapters 5 through 7, and specific answers or themes are referred to in these sections.

### **3.2 Validate Via “Case Study” Analysis**

Variation analysis was conducted on the cargo floor for the new airplane during and after the creation of the whitepaper. It was the intent to develop best practices, discover useful tools and processes, and then apply these to the analysis to validate or evaluate their performance.

This analysis was then presented to all affected teams to stand as its own body of work, as well as to test the effectiveness of variation analysis in driving business and engineering decisions within the company. Two case studies were ultimately conducted and presented.

The initial cargo floor case study is presented fully in Chapter 4.

### **3.3 Close the Loops**

This section discusses how the information loops around the whitepaper and case studies, and around the organization and VRM plan, were closed to leave no loose ends.

During the wrap-up phase of the first case study, information and teachings from the case studies were related back into the whitepaper. The whitepaper was then released through the VRM community and to every member of the 7E7 management team. Information from both the whitepaper and the case studies was then discussed in one-on-one sessions with managers to heighten awareness and answer questions.

Those with further questions were directed to the ASIT team and their VRM plan in order to close the information loop and allow the process to continue in its intent, without the need for the author to remain in the process.

The final case study did not conclude until after the whitepaper was distributed throughout the organization, and was not discussed at length outside the ASIT and FAD teams. It will be discussed in the conclusion of this thesis.

### **3.4 Determine if Problem is “Solved”**

This thesis will discuss metrics and milestones The Boeing Company can use to determine if VRM has been a success on the 7E7, but metrics for determining the success of this thesis or the validity of the hypothesis are difficult at best.

Data on the success of the ideas put forth in this document is not available at this time, and realistically could not be obtained until at least the conclusion of the 7E7 development, thereby making validation a subjective measure. The subjective measures used for the purposes of “validation” are:

- Are ASIT members convinced that focusing attention and/or improvement activities on identified processes will contribute to improved VRM performance versus previous VRM efforts



- Is awareness throughout the management structure heightened with respect to VRM issues, and is management convinced identified processes and improvement efforts are valid and will contribute to improved product performance versus previous product development efforts
- Are the conclusions valid across other types of analysis, work efforts, or business needs
- Were the topics, improvement suggestions, and conclusions in accordance with experience and results from one or both of the case studies

The degree to which the work comprising this thesis “solved” Boeing’s issues will be discussed in depth in Chapter 9.

### **3.5 Summary**

This chapter discussed the methods employed to attack the problem and validate the hypothesis. Despite the issues involved with a scientific validation of the material presented, the findings and the examples brought forth through the case studies will show clear actions and considerations useful during a VRM implementation.

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## Chapter 4: “Case Study” – 7E7 Cargo Floor

This chapter describes the cargo floor case study. After a situational overview, the process steps and tools will be described, along with the method of communicating the results. Additionally, the success of the project will be discussed from an effectiveness standpoint.

### 4.1 Problem Statement

The new 7E7 aircraft has a requirement to be faster and less expensive to manufacture. The cargo area was identified as a subsystem that could have significant time and cost improvement from proper understanding of key characteristics and allocation of tolerances.

The cargo area of most commercial jets is actually broken into two separate areas, the forward and aft, which are located below the passenger deck, or main deck. In a widebody aircraft such as the 7E7, the cargo areas are electromechanical systems designed to move cargo containers or cargo pallets from the cargo door into position, lock the cargo into place for safe flight, and then transport the cargo back to the door for removal.

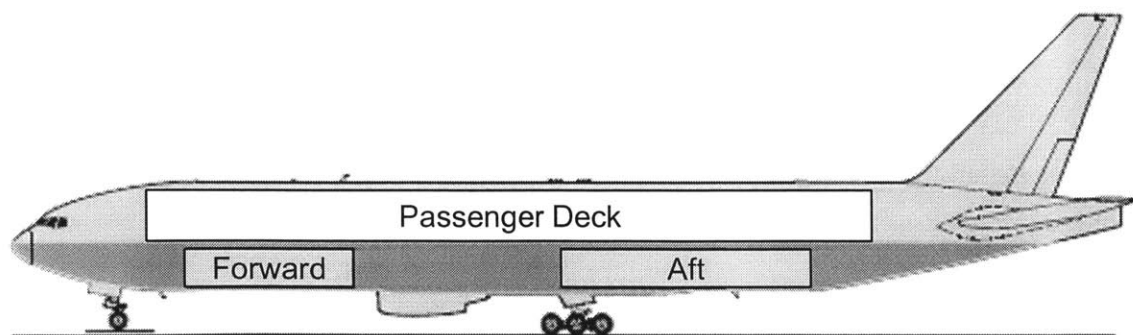
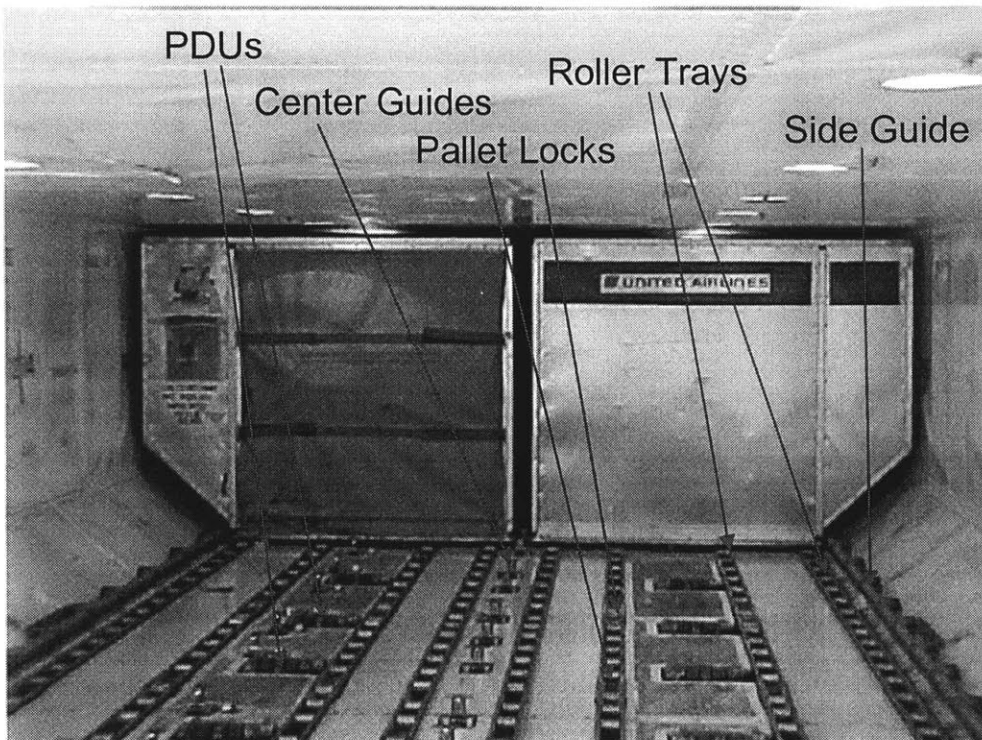


Figure 2: Common layout of main deck and lower cargo areas

The major parts of the cargo area are the roller trays, which hold and transport the cargo, and power drive units (PDUs) which provide the power to propel the cargo along the roller trays, and the pallet locks, which are located in the roller trays and flip up to constrain the motion of cargo during flight. The side and center guides channel the cargo into the proper location during load and unload, and also serve to constrain the cargo's motion during flight.



**Figure 3: Sample widebody cargo area**

Additionally, investigation into a new order of assembly was needed to validate the ability to install the aft cargo system in two separate parts of the fuselage and then join the fuselage with the cargo system already inside.

#### **4.2 Identification**

With the scope and intent of the project defined, the process of requirement identification, key characteristics identification, and flowdown creation began.

Requirements had been gathered by the cargo systems group in preparation for the analysis. Requirements were assembled from Boeing internal documents, engineering experience, and industry guidelines such as NAS 3610, a document created by the Aerospace Industry Association that outlines flight safety requirements for cargo (1990).

Requirements were grouped into tiers, with Tier 1 being the most general grouping and Tier 3 being the individual requirements. Reasons for the requirement were also listed to help explain intent on the less obvious requirements. A single example of a requirement is shown in Table 4.

**Table 4: Example cargo analysis requirement**

Tier 1	Tier 2	Tier 3	Reason
Restrain Cargo	Base Restraints (NAS3610)	Distance between side guides, center guides, and rollout stops	Constrain container/pallet side to side (horizontally)

The 47 requirements identified for this study were then reorganized into 64 part or part-to-part requirements that could be measured and analyzed. With the help of the cargo engineers and some data from the 777 program, a list of 21 potential key characteristics was created. An example of three potential KCs is shown in Table 5, which are labeled as measurements.

**Table 5: Example part-to-part measurements for analysis**

Part	Tier 3	Reason	Measurement
Center guides	Distance to side guide	Constrain container/pallet side to side (horizontally)	Length – LSideGuide → CenterGuide Length – RSideGuide → CenterGuide
	Distance to rollout stop	Constrain container/pallet side to side (horizontally)	Length – CenterGuide → RollOutStop

A simple flowdown was then created to define the interaction of the key characteristics. Once this definition was completed the team agreed to proceed forward with an analysis based on the flowdown. The flowdown, KCs, and list of measurements were then used to build an analytical model of the cargo system.

### **4.3 Assessment**

In order to assess the probability of defects and each KC's contribution to defects, two tools were used to model the cargo area: Microsoft Excel and Dassault 3DCS. After building and populating the models with the proper information, each KC was ranked in importance and the results documented.

The two tools were chosen for their availability within the company as well as their unique strengths and weaknesses. Excel is familiar to nearly all engineers and no special training is needed in order to create sophisticated models. It is, however, easy for even experts to make minor mistakes that could drastically affect the validity of the model. 3DCS is a program that uses solid models created in Catia to assess the effects of tolerances on variation. An expert can create accurate models relatively quickly even with a great deal of complexity, but beginning users can equally easily create models that appear to model the environment properly, but are in fact highly inaccurate.

#### **4.3.1 The Excel Model**

The Excel model was created using both worst case scenario and root sum squared methods. Both methods were chosen to allow a richer understanding of the results and the robustness of the tolerance scheme.

Using the geometries of the relevant parts in the cargo area a coordinate system was created to define the nominal locations of parts, holes, bolts, and other important features of the cargo system. The cargo system is laid out from two datum points, and these points were entered, and the tolerance chain laid out throughout all the features in three dimensions. All tolerances, lengths, and other variables were entered into a column where they could be viewed and edited with minimal effort.

Again wherever it was available tolerance and capability data was taken from the 777 program and used in the creation of the model. Where tolerances had already been set on

the 7E7, those numbers were used, and where no data was available, experts were consulted and asked to provide a best guess. It should be noted as the program advances and capability information becomes more specific, the model can be updated very easily to reflect the better information, and will in turn produce better, more accurate results.

In order to make the results understandable to those unfamiliar with the inner workings of the model the results were displayed in the approximate layout of the cargo area with green or red highlighting to relay acceptable or not acceptable variations based on the tolerances. The display format of the model is shown with a hypothetical data set in Figure 4.

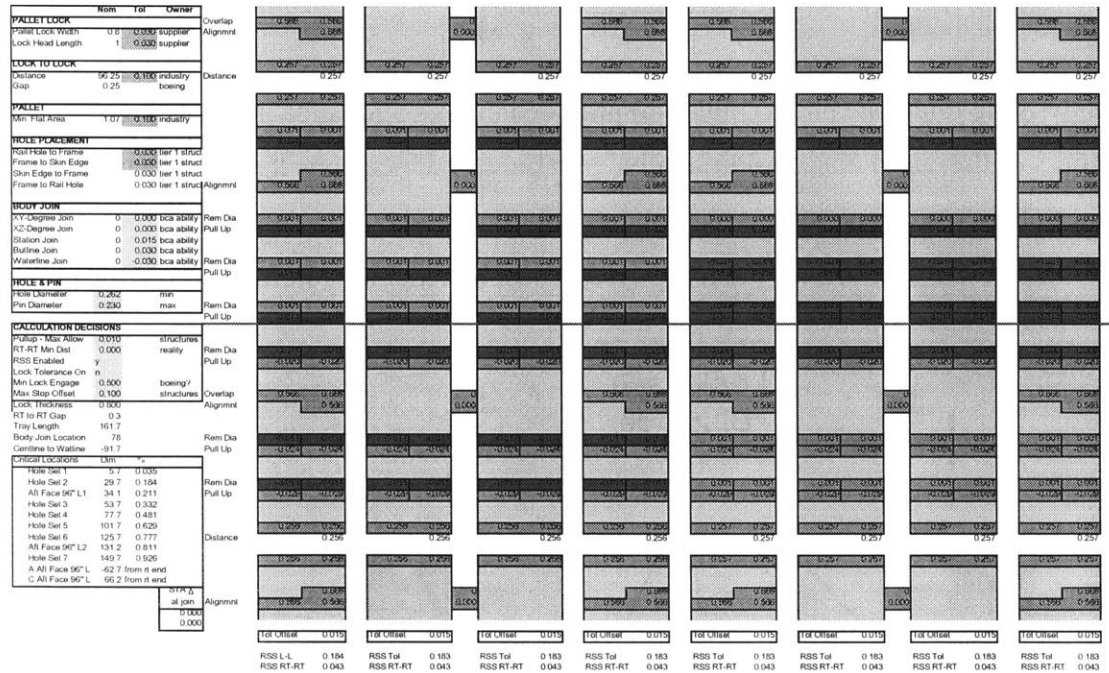


Figure 4: Excel model with sample data

Cost data was not made available during this study, so probability and severity of defects were used to assess risk and prioritize. The results of the study were documented and presented to the affected groups.

While all the results cannot be published, one dimension had the clearest effect on system performance and quality. The pallet locks, and more specifically the distance from pallet lock-face to pallet lock-face was the single most critical dimension in the cargo area.

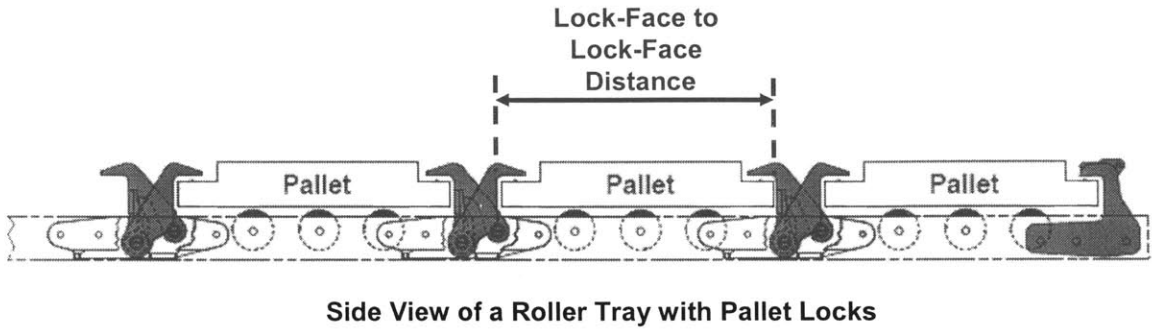


Figure 5: View of roller tray and lock-face to lock-face distance

The underlying tolerance chain (Figure 6) provided many options for improving the robustness of the cargo area. Additionally, variations to dimensions that were not in this tolerance chain were generally found to have little or no effect on system performance, and provided many options for reducing system cost by reducing tolerance requirements.

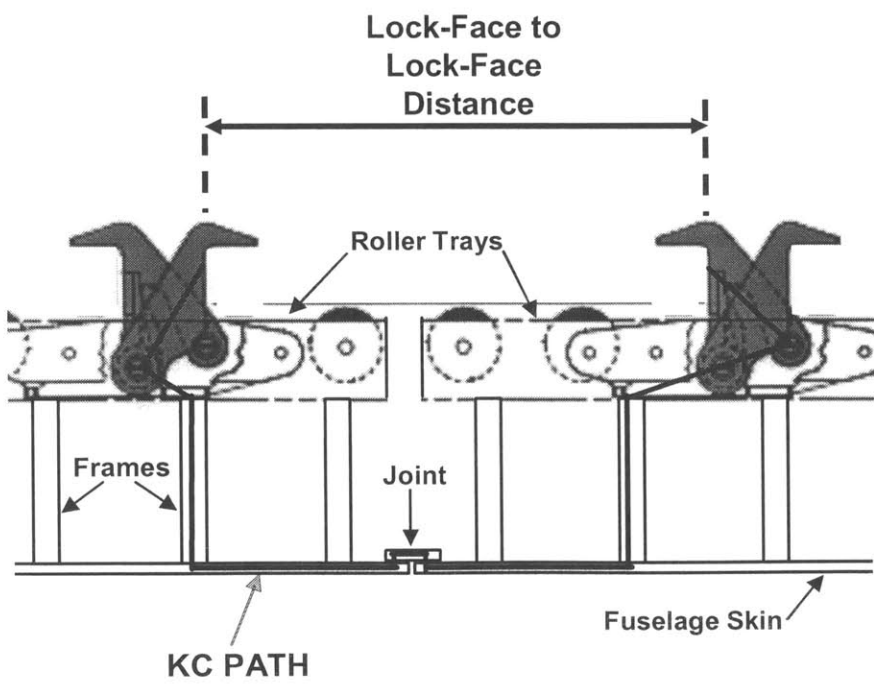


Figure 6 Path over which tolerances must be held to deliver the Lock-Face to Lock-Face Distance KC



### **4.3.2 The Catia 3DCS Model**

The Catia 3DCS model was intended to be a simplified version of the actual cargo system; however, it was also intended to analyze the effects of variation on cargo in motion along the cargo floor. This added complexity proved to be too great for Catia's capability, and ultimately the model was abandoned.

Despite the inability to fully define the cargo system, enough information was collected from a subset of measurements to lend some credibility to the accuracy of the Excel model. Additionally, the attempt to push the capability boundaries of Catia 3DCS and the Catia DMU Kinematics package provided usable data on where functionality is limited, and what steps can be taken to improve analysis capabilities.

### **4.4 Mitigation**

Multiple mitigation strategies were analyzed based on the models. Changes to the tolerance scheme, part redesigns, tooling redesigns, and assembly process changes were all investigated.

Internal experts both from engineering and the production floor were involved in creating the mitigation strategies. Additionally, Delta Airlines cargo handlers were contacted to get users' perspectives on positive and negative aspects of current cargo systems. This information, combined with watching them use the Boeing 767 cargo system at Sea-Tac airport, was used in the generation of additional strategies.

### **4.5 Communication**

Members of the cargo systems group, ASIT team, and several people responsible for variation risk management from other teams were invited to a meeting to discuss the results of the analysis and the mitigation strategies with the most promise. The

presentation walked through the steps taken, results at each point, and outlined the need to move forward on one or many of the mitigation strategies.

One of the steps in the presentation showed how previous analysis efforts had been flawed, causing many engineers to rely on faulty data. Because the previous analysis was done by the cargo systems group, and because they presumably did not like hearing they had made mistakes, several people in attendance tuned out the remainder of the presentation or attempted to discredit the validity of the analysis and findings.

Although this behavior hindered the communication of the mitigation strategy, and unintentionally biased those responsible for deciding which mitigation strategy to pursue, at least one proposed strategy has been incorporated into the system design.

Interestingly, the mitigation strategy chosen was not a direct product of the variation analysis, but rather by common sense. Each cargo area has eight rows of rails running the length of the area which support and transport the cargo. Pallets lay across all eight rails, while cargo containers rest on four rails each. The number of rails is not structurally driven, but simply must hold and transfer the weight of the cargo to the airframe while allowing for proper translation and restraint of the cargo.

Each rail attaches to the airframe roughly every two feet with four screws. The holes must be drilled into the frame using tooling, then the rails are attached with the screws. That makes for eight times the drilling operations, part numbers, material handling, and attachments of a single rail. Six rails (of slightly increased size) could achieve all the functionality of eight rails with no effect on performance. In short, by removing two rails and redistributing the remaining rails across the width of the plane, a major part of the cargo system becomes  $\frac{1}{4}$  less expensive,  $\frac{1}{4}$  lighter (roughly), and  $\frac{1}{4}$  faster to install than the current design.

## **4.6 Project Results**

This case study produced five mitigation strategies, detailed tolerance information for many subsystems of the cargo area, and the critical system requirements for an in-depth study of the body join that the cargo system would have to account for. The result to the 7E7 was that a single mitigation strategy was adopted while the others, along with the tolerance information, were widely ignored. The body join analysis proceeded and produced a great deal of information.

Some people might be tempted to look at the net result of the cargo floor analysis and declare it a failure. While information was generated that will never be used, the return on investment for the analysis is astronomically high.

Several people have pointed to the fact that the one mitigation strategy accepted did not come from the mathematical analysis, but rather from common sense, as a reason why the VRM activity was not needed. It should be noted, however, that the need to think through all aspects of the cargo system and the time spent on VRM activities are what sparked the realization, and without the effort it is unlikely the mitigation strategy would have been presented or executed.

Finally, the level of detail needed to complete the cargo system analysis exposed a lack of understanding around the details of the body join. That realization launched a body join VRM analysis that went on to provide a richer understanding of the joints and aided in further decision making. Without the cargo analysis, the need for the body join analysis would not have been discovered until much later in the development process, at which point any analysis might have had limited time to effect much change in the decision making process.

While there were failures in the process, the VRM activities provided a better than average ROI, and made the end product better and less expensive to manufacture.

#### **4.7 Conclusion**

Rather than focus on the failures or successes, or degrees thereof, it was the intent to draw meaning from what happened, and derive actionable recommendations from this. It is the assertion of this thesis that improvements to VRM-specific tools will generate lower than expected returns until improvements are made in information management, management and organizational support of VRM, and process improvements for both VRM tasks and the use of VRM data.

With reasonable personnel expense and minimal technology expense, even one accepted mitigation strategy made the project a financial success. However, contrary to normal logic, more money or effort put into VRM would have generated little or no additional gain. In fact, the VRM activity already generated more useful information than was utilized, and that information remains valid and usable.

Processes that improve the results of VRM activities may have generated information or mitigation strategies that were not generated and would have been accepted by the 7E7 program. But since information was generated that wasn't used, it is argued here that a more efficient use of effort or funds would be to improve the manner information is stored, used, and distributed, along with better use and definition around initiatives, metrics, and accountability.

## **Chapter 5: Lessons Overview**

The following three chapters will detail lessons in information management, management and organizational support, and processes. This chapter puts a framework around the next lessons in the next three chapters.

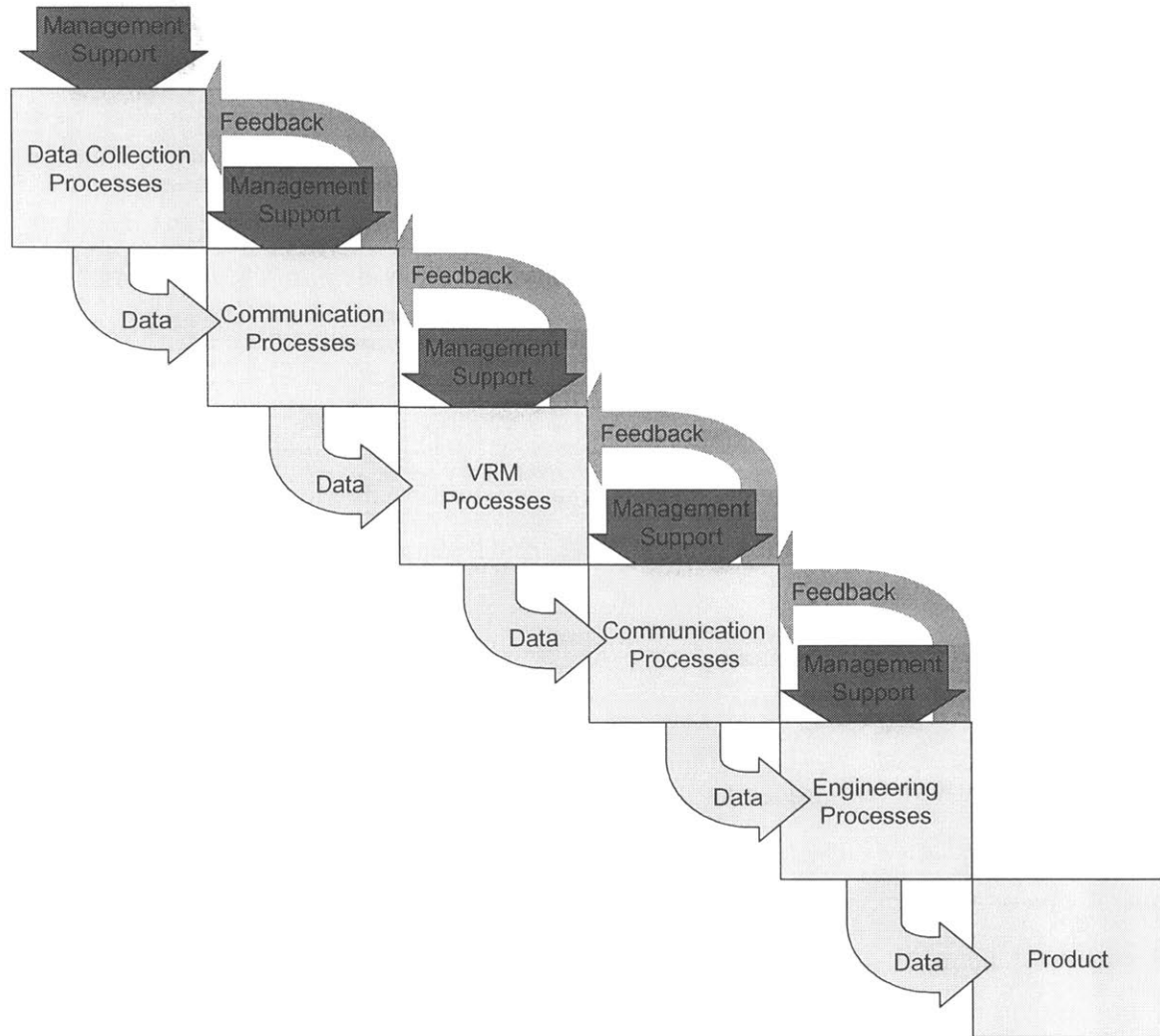
The lessons presented in the next chapters integrate the interviews conducted at Boeing, the whitepaper findings, the cargo floor case study, and the body join VRM activities. It is the intent of these chapters to provide examples from Boeing and present lessons that can be applied at any company. Additionally, several readers of the whitepaper noticed the majority of the VRM lessons applied almost directly to other initiatives they had been a part of. It is the hope that readers of this thesis will also be able to extract the lessons from VRM and generalize them for use in other initiatives or aspects of business.

### **5.1 The Model**

The product development process is a compilation of many sub-processes, each using and generating data that influences the final product. In order to maximize the benefit of the overall chain, each link must be as strong as the others. It is important to note that the data collection, VRM, and engineering processes can be impeccably strong, but if the communication processes, data management, and management support are not in place and effectively applied, the overall impact these processes have on the product will be greatly limited. A visual representation of this process can be seen in Figure 6, and will be explained in the following two subsections.

It is cost savings and quality improvement of the product that VRM is responsible for, and ultimately judged by. The best information, analysis, and mitigation strategies will not affect the product if the overall product development process isn't prepared for the information or responsible for incorporating it in the product. Because of the need to take the holistic view of the product development process, lessons in how to properly organize

these key aspects of the overall process will be investigated in the following three chapters.



**Figure 7: Interplay of information, management, and processes**

### 5.1.1 The Processes

The square boxes in the process diagram represent the major processes in the product development cycle, from a VRM perspective. It is the intent, however, for this model to remain valid if the “VRM Processes” step is removed and replaced with any other type of analysis or engineering support process.

The first process is data collection. This can be any method of collection, ranging from an internet search to a real-time Statistical Process Control feed, but for the general VRM case it should be looked at as the methods by which process capability data is collected.

The second and fourth steps are communication processes. This is to highlight two facts in particular, the first being information gathered and not communicated is wasted information, and the second being ineffective communication can impede the transfer of knowledge, reduce the amount of information used or comprehended, and alter the message of the data to the point where it is misunderstood or misused. Any of these outcomes diminish the ability of the following process to properly contribute to the design of the process.

Communication processes such as phone calls, emails, and conversations may be difficult to manage, but the methods by which people access databases, present information in meetings or presentations, or construct a case for a contentious information can greatly effect the understanding or use of the data, and can be managed.

VRM processes have been and will be further discussed in the paper, and engineering processes are too company-specific to try to address here, but both of these processes are part of the overall design processes and their ability to respond and contribute to each other is important.

### **5.1.2 The Interactions**

Management support, data, and feedback are shown as the three types of arrows in Figure 6. The data must find its way into the processes in some way or another. It can be an automatic entry into a database or a chart in a powerpoint presentation, but there must be some mechanism that takes the data in its raw form and gets it into a form that can be communicated. It is important to note that the data going into a communication process is not necessarily the same data coming out of that process. This situation can be mitigated in several ways, such as determining the proper format for data entry or data

communication, but it should not be assumed that data is not open to misinterpretation or mistakes. It is also a key part of this model that data is generated, modified, communicated, modified, and so on until finally a product is created. It is the opinion of this paper that product development is data driven in some form, even if the data is merely an engineer's gut feeling or proclivity.

Management support acts on each process in order to drive actions and results. It is the variation in amount of management support and pressure on each individual process that can create imbalances and optimize a piece at the cost of the whole. Not to say that each process requires the same amount of support, but "the right amount" of support depending on the company, the people, and any number of other factors. It was determined that management supports the product by supporting the processes, and not by "supporting" the inanimate product, so there is no management support arrow for the product.

Feedback is an important part of any process. One failing of this diagram is that it became too complex to show that engineering processes can provide feedback to data collection without going through VRM, but the general point should remain clear. Each process must react to the positive, negative, important, and even unimportant feedback from the other processes, however, once again, the communication processes used for feedback can have a large affect on the way the feedback gets interpreted and therefore acted upon by the other groups. Lastly, while the product should "feed back" into the other processes, it was determined a non-living object wouldn't actively provide feedback to the processes and organizations, so for simplicity sake no feedback path is shown here.



## **Chapter 6: Lessons in Information Management**

Managing critical information is something Boeing knows how to do, but it can be observed Boeing does not always realize what constitutes critical information.

Requirements, Key Characteristics, and Process Capability are critical to developing cost effective parts that assemble with robust quality.

Proper identification, organization, and communication of requirements affect every aspect of the design process. Without good requirements, engineering will not be able to identify and subsequently meet customer needs. Failure to achieve customer satisfaction will result in potential customers choosing competing products.

Key characteristics can only be identified properly through analysis and understanding of requirements. Without proper identification of KCs, engineering will not be able to understand and eliminate the significant effects of variation on parts and assemblies, and manufacturing cost will increase dramatically.

Failure to track and understand process capability, or process performance, allows excessive variation to continue in production without a plan or means to reduce it. Identification of and management of key characteristics will limit costly measurements to only critical areas while reducing the cost of quality and ensuring quality improves dramatically. Failure to track critical dimensions opens the door for quality defects.

Incorrect or non-existent process capability information makes proper identification of key characteristics more difficult, which leads back to increased measurement and production costs and decreased quality. This loop shows the interrelation of these three types of information, and underscores the criticality of properly managing the information.

For a graphical representation of how R&Os, KCs, and Process Capability Data (PCD) relate to each other, as well as how they affect production costs and quality, see Figure 7.

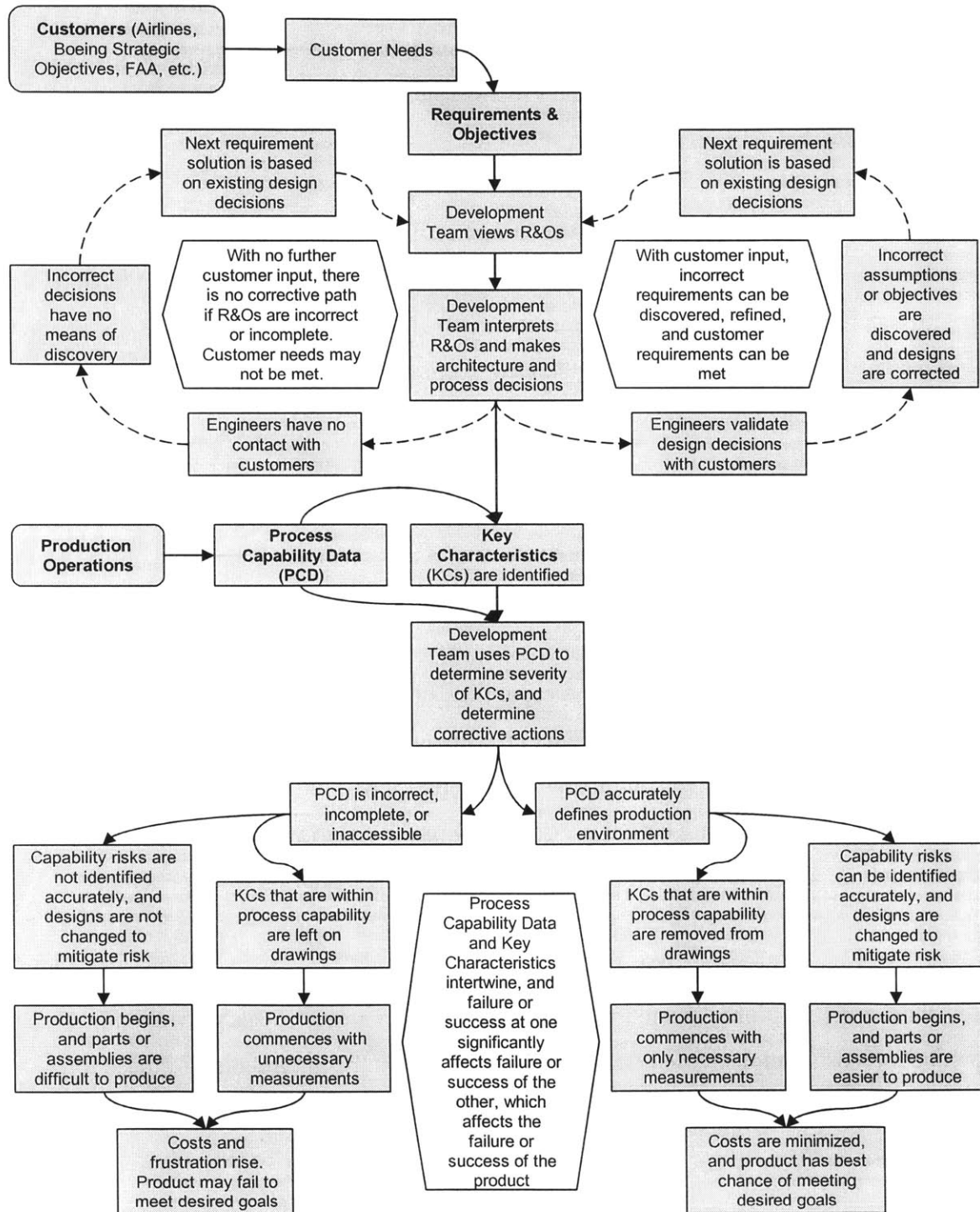


Figure 8: Relational diagram of R&Os, KCs, and Process Capability Data

## 6.1 Requirements

### 6.1.1 Requirements Definition Process

Each interviewee was asked one or more questions intended to determine how requirements were defined and handed off to a product team. Three answers were the most common: the DR&O<sup>2</sup> (Design Requirements & Objectives) document, Aero Department communications, and previous aircraft.

Some of the interviewees mentioned the requirements came from customers, but didn't know the process used to translate customer requirements into engineering requirements. It was clear very few engineers have direct contact with customers. Lack of customer interaction forces engineers to, on their own, interpret and determine intent of unclear or insufficient requirements. This potential disconnect often leads to unmet customer requirements. Clear and concise requirements are critical to proper design and the avoidance of unmet customer needs.

The reliance on requirements from past projects was evident and to some degree disconcerting. More than half of the interviews spent some time talking about requirements carried over from past programs that were not understood, could not be explained, but could not be removed.

Interviews indicated an AIP (Airplane Integration Plan) worked well for housing VRM-related requirements. This document has no authority, however, and was only used as a communication tool within the teams. It holds limited information, and is a duplicate of more detailed information housed and owned at other locations.

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<sup>2</sup> An Example Entry from a requirements & objectives (R&O) document is included below for reference:

Major end items delivered to Final Assembly should utilize simple joining and holding/transport fixtures that are provisioned for multiple models. [BO-BRO138]  
*Assumptions/Rationale* Major component assembly, traditionally using large stationary tools, will be accomplished using modern assembly methods and simple, movable, and multi-function (assembly/transport) fixtures. Reduces non-recurring and recurring costs.

## 7E7 Requirements Locations

A requirements database (DOORS) holds all Tier 0, Tier 1, and Tier 2 requirements and objectives for the 7E7 program. Regulations, requirements, objectives, and design philosophies are entered into the database, potentially through such documents as the DR&O, BR&O (Build Requirements & Objectives), and MR&O (Marketing Requirements & Objectives). These are then held and parsed into the AR&O (Airplane Requirements & Objectives) for Tier 0 requirements, and team-specific SR&O (System Requirements & Objectives) for Tier 1 and lower requirements.

After the creation of the AR&O and SR&O database reports, the other R&O documents maintain authority, but maintenance and update tasks are confined to the Airplane and System R&O documents, as it is now the system of record<sup>3</sup>.

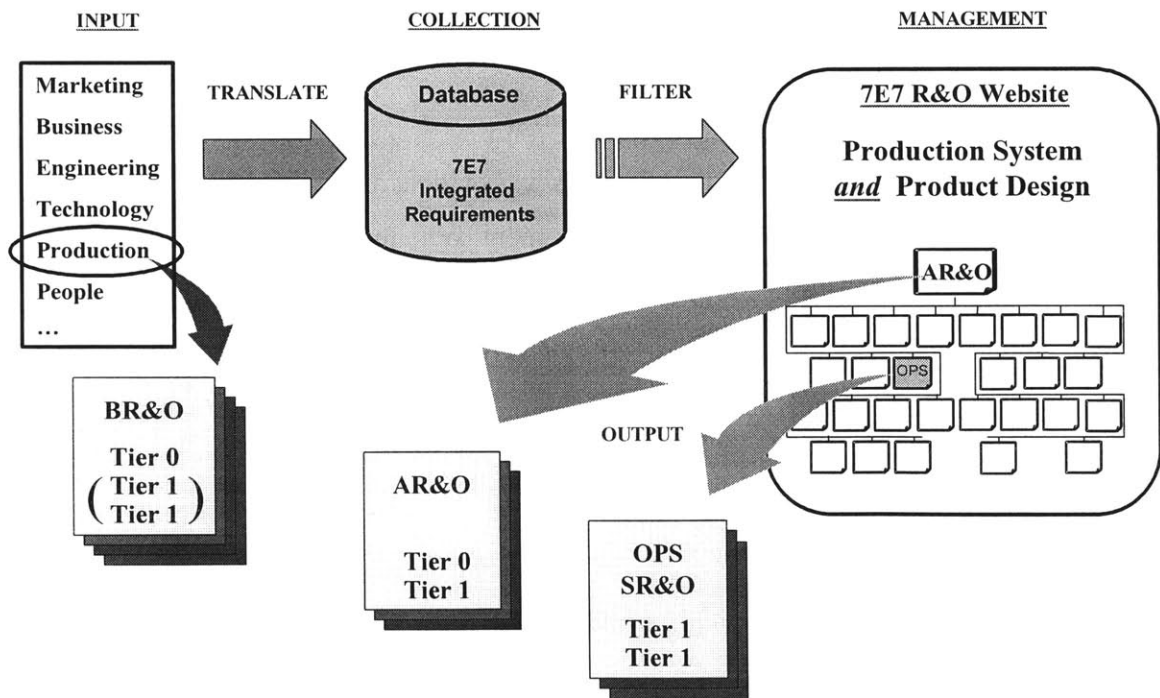


Figure 9: Inputs and Outputs of the DOORS database

All requirements and objectives contain attributes that detail the compliance owner, affected owners, and assumptions and rationale. These attributes are intended to provide, but do not always provide, the information necessary for an engineer to determine the reasoning behind a requirement or objective, and identify the group to approach for any further inquiries.

The Product Definition is a collection of documents that detail the design of the aircraft, its bill of materials, and its build plan. This system of documents resides outside the DOORS database, and is the authority for all developed aspects of the completed airplane definition. Developed aspects may include specific requirements levied by the team on the design, such as material requirements or tensile strength of a part.

### **6.1.2 Requirements vs. Objectives**

One problem several interviews uncovered was the inconsistency in correctly categorizing requirements and objectives. Boeing's DOORS system defines a requirement as "a feature or condition that must be satisfied to achieve program and product goals." DOORS defines objectives as "features or improvements deemed important to the degree that they add positive net value; often these are 'stretch' goals that become requirements given adequate cost/benefit information. Often, goals that are only objectives are listed as requirements for the program."

Here is an example of the problem. A requirement might state excrescence drag<sup>4</sup> needs to be lower than some number. An objective is added as a means to achieve the requirement, stating no gap should exceed 30-thousandths of an inch. However, the 30-thousandths objective becomes a requirement, and gaps that contribute little or no drag are held to the new requirement despite added production cost. Making the objective a requirement forces an engineer into a potentially sub-optimal solution that might be more

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<sup>3</sup> The "system of record" is the document or data location that is the authority. Information in the system of record is by default correct, and discrepancies or disagreements between systems will be settled in favor of the system of record.

costly and less effective than making some 25-thousandths and some 35-thousandths gaps.

The lesson pulled from the interviews is twofold. First, a requirement is something that will hold product release until it has been met, and anything short of that is an objective. Second, if engineers understand the purpose and reasoning behind a goal it will likely be solved in the most effective way, but if an objective becomes a sub-optimal mandate, the metrics and incentives in place drive an engineer to follow the letter of the requirement with little thought on improvement. Worse, a requirement that lacks reasoning and definition carries with it a high likelihood of becoming one of the many poorly understood “requirements” that get passed from program to program, driving the wrong behavior and costing untold sums every time.

### **6.1.3 What to learn**

Requirements and objectives are critical to meeting the needs of customers, regulations, and the corporation. They must be managed in a manner that makes them clear, consistent, and readily available in order to speed and support the decision making process. Steps taken to manage objectives, the system of record, and the methods of communication will aid in the making timely, effective decisions.

### **Manage Objectives**

Almost everyone agrees that objectives are often inaccurately communicated as requirements. Requirements are rarely, if ever, incorrectly communicated as objectives. Some feel this situation arises because objectives are often times ignored or set aside in an effort to meet all the requirements by a deadline. This may be true, but it is unacceptable to “upgrade” an objective to a requirement just to get attention drawn to it.

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<sup>4</sup> Excrescence drag is drag due to such excrescences as grooves, ridges and steps, rivets, and cylinders and stub wings immersed in the boundary layer (as defined by Engineering Sciences Data Unit).

Objectives should justify their importance by including actual cost or opportunity cost data. It is often difficult to quantify either of these costs, but it is inefficient to ignore this important analysis and elect instead just to make the objective a requirement so that it gets more attention. This action takes focus off true requirements, and still does not help engineers or organizations determine the relative cost of missing or importance of meeting objectives.

Identifying requirements and objectives is not a science, and perfection may not be attainable, but the following simple rules will help in the identification process.

- If failure to meet the requirement will not delay or cancel the project, it is an objective
- If the requirement is not defensible with data or customer information, it is an objective until such time as the data exists
- If the requirement specifies a solution (i.e. a gap must be 30-thousandths at a specific joint) is either an objective or a derived requirement, and should be labeled as such

### **Manage the System of Record**

Many companies have multiple locations for data, or change the location of the system of record as a program or the data progresses. In most cases Boeing has reduced to one stable system of record, but in some instances there are still multiple or undefined systems of record. Replication often times introduces errors or omissions in one or the other locations, and can lead to confusion over which of the locations is the system of record. Having two systems of record for the same data is dangerous for integrity and ownership reasons, and should be avoided if at all possible. In order to maintain integrity of data and ensure the proper data is used at the proper time, there should be only one system of record, or one system for a particular data type, and it should remain unchanged for the duration of the project.

Additionally, all members should readily know the systems of record for various data types. If they do not, this should be cause for concern moving forward, and reeducation on proper requirements referencing may be needed to ensure all teams are working from the same set of requirements.

## **Manage the Method of Communication**

Groups or organizations that create their own documentation for requirements need to be stopped. Team-specific documents may serve a temporary communication purpose, but documentation that becomes a team's system of record tends to get updated infrequently and introduces an unnecessary failure mode for the requirements process. If the systems of record do not report necessary data in a format acceptable to the overall team, effort should be spent improving the system of record rather than on dangerous and inefficient workarounds.

## **6.2 Key Characteristics**

### **6.2.1 Past**

The proper identification of Key Characteristics is critical to VRM processes. Understanding the significance of a KC is critical to properly identifying and communicating a KC. Boeing has, by most people's recollection, done this poorly. The silver lining is that now people have very good ideas on what KCs should be.

The term Key Characteristic has been around Boeing for roughly 30 years by some people's memory, and in that time its definition and focus has changed frequently. It has had several definitions and focuses, and no one seems to agree on what the definition was at any particular point in time.



Two interviewees related a story of a KC seminar at MIT several Boeing employees attended. At the end of the multi-day event, Boeing still had no consensus on what a KC was.

During the 777 program, KCs were everywhere. One story aided in explaining the situation. A high-level manager heard a pitch extolling the virtues of KCs but warning never to have more than five on a part. The manager somehow mistook or miscommunicated the lesson and a requirement was implemented that each part have at least five KCs. This story was met with nods of agreement or fascination by all of the subsequent 777 engineers I spoke with, but it was not disputed.

Production was responsible for measuring the KCs, and after incurring the cost without tangible benefit for as long as they could stand, revolted and eliminated most measurements altogether.

The story on the 737 Next Generation is similar. Having learned from the 777 experience, the design team implemented fewer KCs, but still ran into eventual resistance from production as the effort and cost of tracking the large number of measurements continued. Those interviewees appearing the most knowledgeable about both the 777 and 737 NG projects raised concern that the average engineer didn't fully understand what a KC is. This lack of education caused KCs to be incorrectly identified and led to many of the problems seen in production.

Two interviewees expressed a desire to hold engineering accountable for KCs indicated on drawings. One interviewee recalled a Ford engineer claiming they had to provide reasoning for any KC as well as the budget to account for it in the factory. This particular method of holding engineering accountable for its Key Characteristics may have only been mentioned by two, but several more felt there was a general lack of accountability among engineering for correctly identifying KCs.

### 6.2.2 Present

Focus and intent may have changed significantly in the past, but different Boeing locations appear to be converging. Roughly a third of the interviewees directly said a key characteristic should only exist when variation susceptibility can't be designed out. Nearly all remaining interviewees made claims that past programs overused KCs, and the Boeing community now understands KCs should be used sparingly.

It should be noted at this point that KCs generally fall into five categories (Thornton, 2003): product KCs, system KCs, assembly KCs, part KCs, and process KCs. An example of a product KC would be excrescence drag, where variation potentially has a large negative effect, but no amount of design creativity will be able to eliminate the KC, and measurement of the KC in production is impractical. All the KCs are important, but most references to KCs in the whitepaper are to part or assembly KCs, such as a critical dimension or stiffness, and this section in particular focus on these types of KCs.

The cost of labeling a KC was a factor in most of the people's minds. Labeling a KC on a drawing brings about actions in the design process along with measurements and inspection in the manufacturing process. This activity cost, while difficult to pinpoint in its entirety, gets multiplied by every single KC identified throughout the airplane.

One interviewee asks people to look at KCs from a manufacturer's perspective. If all dimensions have tolerances applied to them, but a few are labeled as KCs, how are the production personnel supposed to react to the KC essentially telling them "try harder on this dimension?" The point being the typical reaction is no reaction.

A small number of people felt KCs needed to be identified, but not necessarily measured in production. A slightly larger number felt a KC that doesn't need to be measured is likely not a real key characteristic.

### 6.2.3 What to learn

It is important to understand the company's reasons for identifying KCs in order to develop a plan for managing them. Two reasons are prevalent: to aid in designing robust products that reduce negative effects of variation and to identify variation-sensitive dimensions<sup>5</sup> and communicate that to production. The reasons are not mutually exclusive, and it is an assertion of this thesis that both these aims should be adopted and communicated.

If the reason is to identify variation-sensitive dimensions and communicate that to production, production needs to understand the consequences – in terms of cost, performance, or quality – of varying from nominal on each individual KC.

If the reason is to aid in designing robust products that reduce negative effects of variation, engineering needs to focus significant up-front effort in the identification of and subsequent redesign for the removal of KCs through the design process.

While both reasons involve KCs that must be managed, the supporting information that must be managed is different, and the audiences for the information are different. In order to effectively distribute and communicate the information to both engineering and production, multiple interfaces or displays may be necessary to access the KC information, though it should remain a single source rather than multiple sources.

Additionally, the question of when to measure a KC must be addressed. It is suggested that measurements and/or satisfactory Cpk are necessary because of the “risk” component of a KC. The development of a “measurement plan” to assess KC risk in an ongoing manner during production should be undertaken, and the plan enacted to determine if measurements should be taken or not. Because a KC is “high risk” this month does not

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<sup>5</sup> Variation-sensitive dimensions are dimensions that require tolerance limits that are close to the manufacturing process capability. While any tight-tolerance dimension can be considered variation sensitive, it only becomes critical when the manufacturing process is barely capable or incapable of meeting the requirement.

mean it will be next month, and a KC that wasn't deemed "high risk" during product launch may become high risk due to any number of changes in process, personnel, or material.

If KCs are used in development and production, once the identification, analysis, and redesign steps are completed the KCs must be communicated to suppliers or manufacturers in a manner that draws attention AND affects behavior. Loss functions or cost curves can go a long way in this endeavor, but compiling this information can be difficult if not impossible for all KCs. Designs that eliminate all but a necessary few KCs based on actual process capabilities will have more luck drawing proper attention to these dimensions. However, without measurement plans, process improvement plans, and requirements more stringent than tolerance goalposts, KCs will remain tolerance bands indistinguishable from all other dimensions, but with a special note to "try harder here."

### **6.3 Process Capability**

Suppliers and internal manufacturing have been asked for process capability data over the course of many projects and years. No interviewee, nor current ASIT team member, was aware of a current location holding that information or process for acquiring that information.

Process capability databases have existed within the company, but the level of benefit provided was not agreed upon by the interviewees. It is believed Boeing as a company did not see the benefits of process capability databases outweighing the support costs, since none of the interviewees knew of any current process capability databases. Information is available at certain manufacturing locations for certain manufacturing processes, but these information repositories are not well known.

Those familiar with getting process capability information from suppliers agreed that it is not an easy process. Past development projects have used a Request for Process Capability Data (RPCD) document with some success. Those most familiar with the

RPCD described its use as a lengthy iterative process requiring an early start, adding the process must be performed on the majority of piece parts. Complicating its use is the fact that many parts are not assigned to a specific vendor until very late in the process.

Because of this those in need of the data must either query many vendors for process information, even though only one data set will be used, or wait until potentially too far into the process before contacting the actual supplier for data.

Additionally, one interviewee warned that current suppliers are often hesitant to provide process capability data on current Boeing parts because they are worried the data may be used for contractual negotiation in addition to or instead of being used for design work.

### **6.3.1 What to learn**

The constant collection of manufacturing data is critical to providing engineering with an understanding of the point at which their designs become risky or prohibitively expensive. The processes measured and frequency of measurement can be changed or set in a manner to limit costs while still providing benefit.

Short of continual monitoring, the best way to get process information in a manner that benefits the engineers and ultimately the product is to get suppliers, internal and external, involved in the design process early. Bringing shop-floor experts into design meetings is an accepted practice at most companies for almost all major assemblies, and the benefits of that practice extend to sub-assemblies and detail parts. The RPCD is a valuable tool that can be used when co-design is not possible, but having those intimately familiar with process capability during the design process is the best second option to having hard capability data.

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## **Chapter 7: Lessons in Management & Organizational Support**

The appropriate metrics, proper assignment of accountability through those metrics, and appropriate team structure are key enablers for VRM. Breaking the cycle of initiatives, or the tendency for initiatives to replace initiatives - only to get replaced by yet another initiative, is also of utmost importance for VRM. This chapter focuses on these items and their role in shaping the outcome of VRM efforts.

Success or failure of VRM will largely depend on the depth of penetration and the amount of focus it receives from the program. Penetration is achieved either from top management down or from the grassroots up. The 7E7 program does not have the luxury of time necessary for a grassroots effort, so it must get the right kind of management support. Focus is achieved by management support, but setting up the team and organization in a manner conducive to the work required is critical as well.

If sufficient penetration is not achieved, much of the program will continue without gaining any benefit from VRM. If the whole program does not benefit from VRM, it is unlikely the small victories achieved will be enough to convince Boeing of the benefit of VRM. If sufficient focus is not achieved, schedule will dictate behavior and the design will fall back on the known methods for designing an aircraft, many of which are not applicable to the 7E7. VRM will again fail to bring about significant benefit, and will likely follow the path of AQS, HVC, and other initiatives that did not stand the test of time.

Providing the conditions for success is critical to achieving success. Based on interviews, five topics emerged as significant contributors to the failure of past initiatives: metrics, team structure, accountability, training, and the idea of the corporate initiative.

In an effort to help demonstrate the interrelation of these topics, the following flow diagram was created (Figure 9). It shows how initiatives get started and eventually fail

based on metrics and accountability, giving birth to new initiatives. There are other failure modes and other influences, but in an effort to keep it relatively simple this diagram only investigates this portion of the loop.



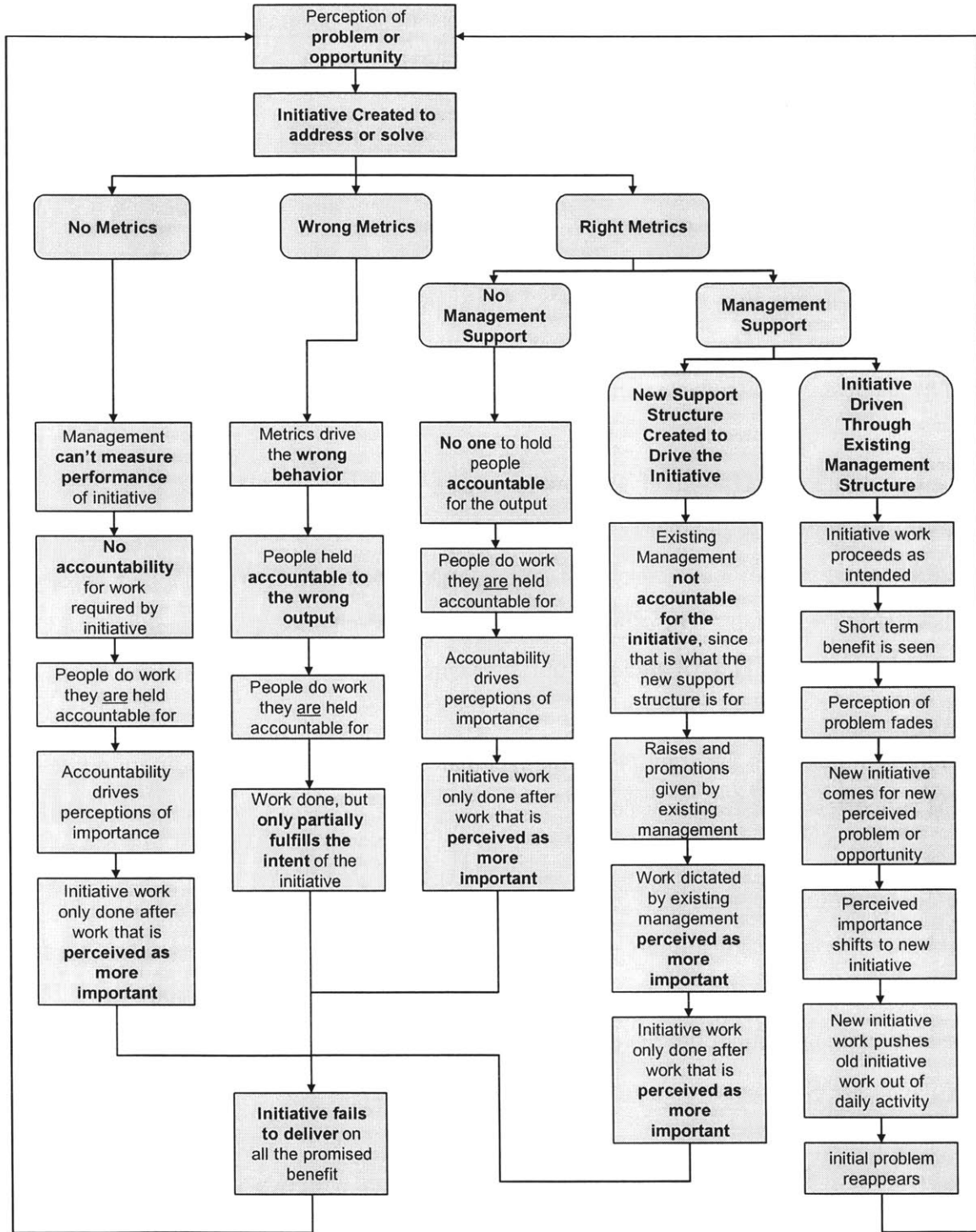


Figure 10: The Initiative Failure Cycle

## 7.1 Initiatives

In order for VRM to achieve significant benefit on the 7E7 program, its purpose, process, and tools must be adopted by the teams. In the past, adoption has been driven via initiatives, such as AQS and HVC.

Those past initiatives, however, have generated two camps around the issue of how to present VRM to the 7E7 team. Roughly half of the interviewees felt in order for VRM to be accepted, an initiative must be declared and a support structure erected to help drive the practice into the team. The others felt VRM should be driven into the team via the current management structure without calling it an initiative.

This dichotomy arises based on perceptions of past VRM initiatives' success, or lack thereof. Attempting to paraphrase, some feel the eventual termination of those initiatives and the lack of current focus equates to failure, and another initiative with a new acronym will suffer the same fate. The others feel focus cannot be attained and change cannot be achieved without the kind of attention initiatives provide.

Adding complexity to the argument is the fact that VRM will not be the only initiative VRM supporters have to worry about.

The 777 program had nearly a dozen initiatives associated with it, each one adding to the workload of those responsible for their execution. The 737 NG had nine. Each of these initiatives were deemed critical to the success of the project, yet by most people's recollection no additional time was allotted for the completion of the initiatives' associated tasks.

Recollection of the initiatives varied between interviewees with experience on these two projects, but none recalled what all the initiatives were, and barely more remembered ever knowing, though most remembered with disdain how many there were.

Unfortunately interviewees were not asked to give a post-mortem on the success of the other initiatives to determine their relative success or discover their fate.

### **7.1.1 Analysis of Initiatives**

Initiatives create focus but have a real and unfortunate side-effect of creating a distinction between “my real job” and “the initiative.” Unless an initiative can clearly demonstrate a reduction in workload, or management actively shifts work or resources to accommodate the initiative, it will be viewed by most as additional work. Additional work, no matter how beneficial and well intentioned, is not something many employees get excited about.

Even if all team members are open to some new tasks or processes, we must consider what will happen if they are given nine initiatives with nine new tasks and processes. A day is 24 hours; a work day is some degree shorter. Nine initiatives plus what someone considers their “real” job don’t fit. Once a person is forced to decide which initiatives seem important and which don’t – without management prioritizing for them - it is a very short path to a decision that all initiatives are equally unimportant. Even if people do not make that last logical step, it is a reality that something among this group of tasks is not going to get done. VRM cannot afford to enter the initiative lottery in the hopes the majority of the team members choose its processes and tasks as most important.

### **7.1.2 Side Effect or Main Effect?**

Much of the previous analysis has pointed to a conclusion that initiatives all end, and usually end without achieving their stated aims. Despite a seemingly worldwide opinion that “corporate officials” and “upper management” don’t know what they are doing (i.e. “Management must be crazy to...”), let’s assume for a moment that they do. There must, then, be a logical answer to why corporations continue to direct money and resources to various initiatives that seem to fail.

A potential answer is that initiatives direct money and resources to awareness and experimentation. Proper data was unfortunately not collected on this aspect, but several people mentioned through the course of interviewing that despite HVC’s apparent failure,

many people who previously dismissed the need to deal with variation during the design process now readily agree it is a problem that needs to be addressed.

Additionally, there are thousands of people scattered through the company now with HVC experience. While the degree of their knowledge varies, they all understand the effects of poor variation management and some methods to control variation. Even those who feel HVC was misguided or flawed have refined their views of how to properly deal with the issue as a direct result of their experience with HVC. That experience and knowledge is incredibly valuable to the success of the 7E7 program, and would not exist within Boeing if not for HVC.

That said: is this refined knowledge and experience simply a side effect of “failed” initiatives or was it the intended output all along? Is management achieving their aims or ignoring their “failures?” Is this thesis going to attempt to answer these two questions?

No.

Whatever the intent, the conclusion regarding initiatives is that they are flawed. There must be a way to gain valuable knowledge without most of the negative side effects past initiatives have suffered from. Negative effects include but are not limited to high budgets, high workload, high dissatisfaction among a significant number of the workers, and, most importantly, not getting the expected benefits.

### **7.1.3 What to learn**

All initiatives are not bad, and rarely will simply “not declaring” an initiative foster adoption in any way. It seems, though, that initiatives are best reserved for short-term projects or ventures where, once they are completed, the initiative is expected to end.

If the goal is high visibility during product development then an initiative with a corresponding central support structure will provide that. The down side to this strategy

is that the VRM initiative will, if the past holds true, run its course and fall by the wayside at the end of the project. This course of action is suggested if the program is concerned no VRM tasks will be pursued without high visibility.

If the goal of the team is more long-term in nature, educating current management on the intent and processes of VRM appears to be the way to go. It may delay adoption slightly, but the concepts will better work their way into the every-day way of doing things.

Direct supervisor pressure and proper workload allocation will serve to blur the line between “my job” and “VRM,” allowing engineers to see VRM tasks and processes as “the way things are done” rather than something “in addition to” the current work.

A relevant example of non-initiative-based adoption is structural analysis. Not all companies need to do structural analysis, and very few companies outside aerospace and civil engineering did significant structural analysis before computer tools advanced to the point of time and cost effectiveness. The work associated to structural analysis was not introduced via an initiative. The need for the analysis was clear, people understood the requirements, and at least at Boeing it quickly became accepted every day practice to conduct that work for each program. VRM and variation analysis are similar to structural analysis. Not all companies need to do it, but many, like Boeing, require or desire a level of performance that can’t be achieved without VRM. If the output of VRM is understood to be equally valuable to that of other analyses, then the tasks and tools should be introduced to companies much like computers, MS Office, and structural analysis were introduced – as necessary tools to properly do the job. No name or initiative required.

## **7.2 Metrics**

Metrics used during past VRM projects were discussed during each interview. The two most common responses about past metrics were that there weren’t any, or that they weren’t the right metrics.

Metrics discussed tended to fall in two categories: those that track progress and those that measure success. Interviewees that did remember metrics recalled progress metrics but no success metrics. There was significant support among the interviewees for metrics or measures to define the goals, objectives, and expectations of VRM, but few examples or ideas of what those metrics should be.

One military program had 28 customer performance measures associated with the program and agreed upon by the customer, and all activity was tracked to those measures throughout the program. Quality and production cycle time were two of the metrics, and VRM activities were tracked and graded based on them. While these measures cannot be “proven” until production begins, the team likened them to weight measures. Every project accurately tracks weight through the development process and has a weight target, or budget, for success from day one. “Why can’t we, with the tools we have, [treat these] in essentially the same way we treat weight?”

Other tracking metrics proposed or remembered included: percent AIP completion, number of joints analyzed, number of KCs identified, and percent completion of plans such as build plans and measurement plans.

Discussion often centered on the difficulty to measure success of VRM. It was pointed out several times that if VRM is done early enough and properly, there is no way of knowing what mistakes you would have made without it. This makes it impossible to know exactly what cost or risk was avoided.

The leading method for attaining this information is to compare the new program to past programs, but VRM is not the only process or procedure that affects quality, cost, and producibility. This often makes it difficult to define the amount or percentage of contribution VRM provides when decisions are influenced by six-sigma, lean, and other processes or initiatives as well.

### **7.2.1 What to learn**

Metrics have many functions, but most generally fall into three categories: control, reporting, and communication. The importance of good metrics that define goals and objectives rather than tasks or processes will help drive and control employee actions. Having those metrics in place during a project will report and communicate progress and aid in the justification of VRM expense.

High priority should be given to the identification and implementation of goal-oriented metrics, as analysis does show failure to define success, measure progress, and quantify ROI leads to unmet goals, unmanaged effort, and process abandonment.

This is not to say that metrics are the key to proper management, in fact they seem to be used too often as a crutch or justification for bad management. Metrics can quickly explain what is important and provide direction, but they can not take the place of proper education and active, informed management.

### **7.3 Accountability**

Driving new processes into the team and setting up the right measures and incentives will fail if accountability is not assigned. Certain people attribute this failure mode to employees' lack of enthusiasm for activities which will neither help their career nor hurt it if the tasks are not completed. Others assign blame to poorly defined roles or team structure, where no one is the ultimate authority and everyone thinks the "other guy is supposed to do that." The other explanation articulated during the interviews was training that leaves people knowledgeable enough to be told what to do, but not knowledgeable enough to figure out what to do, ensuring nothing gets done that isn't explicitly assigned.

### **What to learn**

Successful accountability holds the entire team responsible but defines roles and tasks ultimately assigned to specific team members. High performance teams are able to juggle work that anyone can do to the member with the lightest load at that moment, and assign specific specialized tasks to those resident experts capable of completing them. This requires a manager or management strategy that assigns task accountability to individuals, but assigns deliverable responsibility to the team as a whole. This strategy, executed properly, encourages level-loading of team tasks but does not allow confusion or laziness to break the line of accountability.

### **7.3.1 Alignment**

Management cannot establish metrics and expect people to do more than pay lip service to them unless performance to the metrics provides a clearly stated benefit. This benefit does not have to be financial and shouldn't be a scare tactic, but everyone must know why a metric is in place and what achieving it or falling short of it means to them.

One interviewee recalled a quarterly HVC meeting where people had to update performance or progress of HVC efforts. "Success was defined by getting through the pitch rather than succeeding at the process." The failure of the metrics could have been that the wrong metrics were in place, but a lack of accountability to the existing metrics is evident.

### **What to learn**

Accountability needs to be assigned up the entire management structure. Holding a team accountable for a task or process their manager is not held accountable to places an unhealthy conflict of interest on that manager. Holding a manager accountable for a task or process his or her manager is not held accountable to does the same, and on up through the reporting structure.



Change is best driven from the top down, and the most effective way to enable change is to align all levels to common goals and hold all levels accountable to common measures.

### **7.3.2 Team Structure**

An appropriate team structure is critical for assigning responsibility. Deciding which people are responsible for VRM has far reaching implications and consequences. Three types of team structure have been used in the past. At one extreme is a small core group of VRM experts that work essentially as consultants to the program and conduct the majority of the analysis. The other extreme is to teach everyone on the program to do the VRM tasks. The third structure interviewees had experience with was a mixture, where VRM experts reside on individual teams throughout the program while still coaching the entire team on VRM processes and tools.

#### **Core Group**

This structure has typically been used for short duration projects where there were relatively few available VRM experts and a timeline that prohibited extensive training. Interviewees had mixed opinions about effectiveness.

Experienced people are much more likely to properly execute VRM processes and interpret VRM analysis. Having an expert team responsible for the detailed analysis work ensures accountability and maximizes the probability the analysis will be done correctly.

The problems with this set up are numerous, though. First, it does not scale well. A small core group can only do so much analysis, and as the size or scope of a project grows the amount of work the group can do will stay constant, gating the entire process. Additionally, since they are not familiar with details of the development, it will be difficult for this group to properly prioritize analysis and mitigation efforts as requests for work flow in from several separate teams. Finally, those with experience in this team

structure said the probability of a “who died and put you in charge” attitude throughout the program was much higher than in-team experts. This feeling was presumed to occur because team members submitted a design to the experts and then received changes they need to make back, potentially not understanding why.

### **Everyone Responsible**

By most accounts the structure on the 777 program was to have everyone responsible. It worked well because each team member understood the stated purpose of VRM (HVC at the time) and received training in proper execution. This structure scales very well, as the larger the team gets, the larger the available VRM resource pool gets.

Educating an entire team on VRM, and continuing to educate new members as the team grows, is difficult. Even a full week of training is no substitute for experience, and a team with no experience is not going to perform at an expert level. While there will likely be experts on many of the teams, accountability resides with each member equally in this setup. Several interviewees on teams like this agreed that unless someone took the initiative or was assigned to be a VRM focal point, work was shifted around among equally unskilled team members. If the team was lucky the work got done poorly, if unlucky, it didn't get done at all.

### **Blended Team**

A blended team strategy was proposed by several interviewees. The strategy here is to logically place experts as integral members of the multiple program teams to act as guides and mentors while at the same time educating others as necessary. This strategy requires metrics to be defined at a team level, with the resident expert responsible for the coordination of effort and the team responsible for overall output.

This strategy works well because there are clear focal points responsible for making sure the teams adhere to the proper processes and complete the proper analyses. Because the

experts are part of the team and are more familiar with the product, this structure leads to better analysis and interpretation of analysis, and theoretically this setup is less likely to engender the “who died and put you in charge” reaction. Additionally, having an expert close by will allow for those less knowledgeable or less confident members of the team to conduct simpler analyses while having a readily available resource for brief analysis or process questions. This will presumably increase the quality of work produced by the team.

This strategy can still fail in a number of ways. Scaling up a project can be very difficult if the number of teams exceeds the number of experts. It may also fail if the expert is given no authority to delegate VRM tasks to other team members, who may view all VRM work as the expert’s responsibility. This structure also relies on the VRM expert to be an effective project manager in addition to being technically proficient. Every team that has an expert who is not in possession of both attributes will have to develop its own method for handling the project management aspects of the role. Lastly, communication between experts must be facilitated in some official or unofficial manner to ensure continuity of methodologies, communication of new and improved tools or processes, and minimal splintering of small groups in directions not beneficial for the company.

### **What to learn**

The three options presented are realistic compromises to the unattainable goal of everyone on the program being an expert. The level of intended VRM investment, capability and cohesiveness of the people, and current organizational structure must be taken into account when deciding on a team structure.

In Boeing’s case, a blended team was deemed ideal, partly to organize VRM in a similar way to structural analysis. There is no centrally located structures group, and not everyone on each design team is expected to perform structural analysis. Each team has someone who is capable of doing detailed structural analysis, but everyone is responsible for and capable of identifying when a structural analysis is needed. In addition, every

engineer and manager appreciates the criticality of structural analysis. This is the state VRM should strive for, and setting up the team to enable that is a very important step.

### **7.3.3 Training**

Boeing has invested considerable effort and time to train thousands of people in AQS and HVC over the years, but now finds itself with a lack of VRM expertise. The 7E7 team must now discover a way to most effectively and efficiently use its existing expertise and expand that knowledge base.

Looking at past programs' training, former HVC coaches agreed the training they conducted was good. However, most felt the ideas they tried to get across were either poorly retained or poorly applied. One trainer recalled determining the success of the training class by counting the number of discarded training manuals in the conference room trashcan at the end of class. It tended to fluctuate from large to very large.

Those that felt the training failed to produce results tended not to agree on the reasons behind the failure. One felt the HVC training amounted to a collection of tools, where upon completion of training someone would hopefully know how to use the tools, but without constant supervision would not know when or where to apply those tools. Another felt training failed to instill the sense of urgency with the need for variation analysis, and when schedules got tight people cast aside their training and just struggled to finish drawings. One more HVC and six-sigma trainer felt those leaving training were able to apply the training to known issues, but were still mostly unable to seek out and identify new areas or issues where the training could be applied.

Currently, a division in Wichita is trying to build up their VRM expertise. There is no classroom training. Instead the trainees spend all day each day understanding the concepts and processes of VRM while simultaneously applying the knowledge to variation analyses. Some of the analyses are made up exercises, some are actual analyses needed by various programs. The trainees are co-located with the experts and talk

frequently, asking questions and seeking help at any time during the day. A current trainee three weeks into training felt the most important factor in his education was having the expert a few feet away.

Asked what level of skill was attained after his first week of training, the trainee replied he could maybe make a simple tolerance model, and maybe analyze the result, but that he “wouldn’t be able to learn DM [VRM] in a week.”

If someone three weeks into an intensive one-on-one training schedule feels uncomfortable with the level of skill achieved after a week, it casts doubt on the level of skill attainable in a one-week ten-on-one training session.

### **What to learn**

Building VRM capability will require a company to teach its engineers how to identify areas that are sensitive to variation and to then seek an expert’s help on how to analyze the problem and develop solutions. The company needs to simultaneously reduce the current expert’s workloads and task them with mentoring one to three interested team members with the analysis tools and processes. Initially these students should do the majority of the analysis and mitigation creation under close supervision of the expert, until such time as the workload increases to the point the experts need to conduct analysis as well. The goal is that by this time these few “trainees” are sufficiently comfortable with the analyses that they can conduct them on their own with only minimal guidance and help from the experts.

Training in a classroom setting tends to be expensive and hard to schedule. It becomes ineffective when these attributes drive a graduate-level course to be condensed into a one-week or eight-hour training session. All important aspects of VRM cannot be effectively conveyed in a timeframe most engineers have available for classroom activity, so traditional training should not be used.

However, having everyone's eyes trained to seek out problems and identify them has been a major stumbling block of past initiatives. Without everyone knowledgeable in the processes used to identify product issues, too many issues and opportunities go unnoticed. These unnoticed problems will not receive the attention they need, which in turn causes dissatisfaction with the effectiveness of the initiative or practice. The number of people knowledgeable in the assessment and mitigation processes can and should be much smaller than the number of people able to identify the issues and call those experts to the problems.

As stated in the team structure section, placing current experts on each team will provide a focal point for VRM efforts, but it will also provide a resource for questions about processes and identification of problems that will help adoption and effectiveness of the practices.

#### **7.4 What to learn**

The initiative cycle shown in Figure 9 had no success path shown. Figure 10 shows two potential paths incorporating an overview of all the lessons in this section.

It is suggested that initiatives only be used for short term projects or objectives. If the initiative results are successful and determined useful in the future, an effort should be made to remove the initiative and institutionalize the workload via a new position or job description.

If the objective is longer term in nature, it is suggested an initiative not be set up, and instead work packages and responsibilities be created to legitimize the work, underscore the permanence of the work, and associate a "this is my job and this is how it is done" attitude to the work.

With all the paths proper training or education, metrics, and alignment are critical ingredients for success.

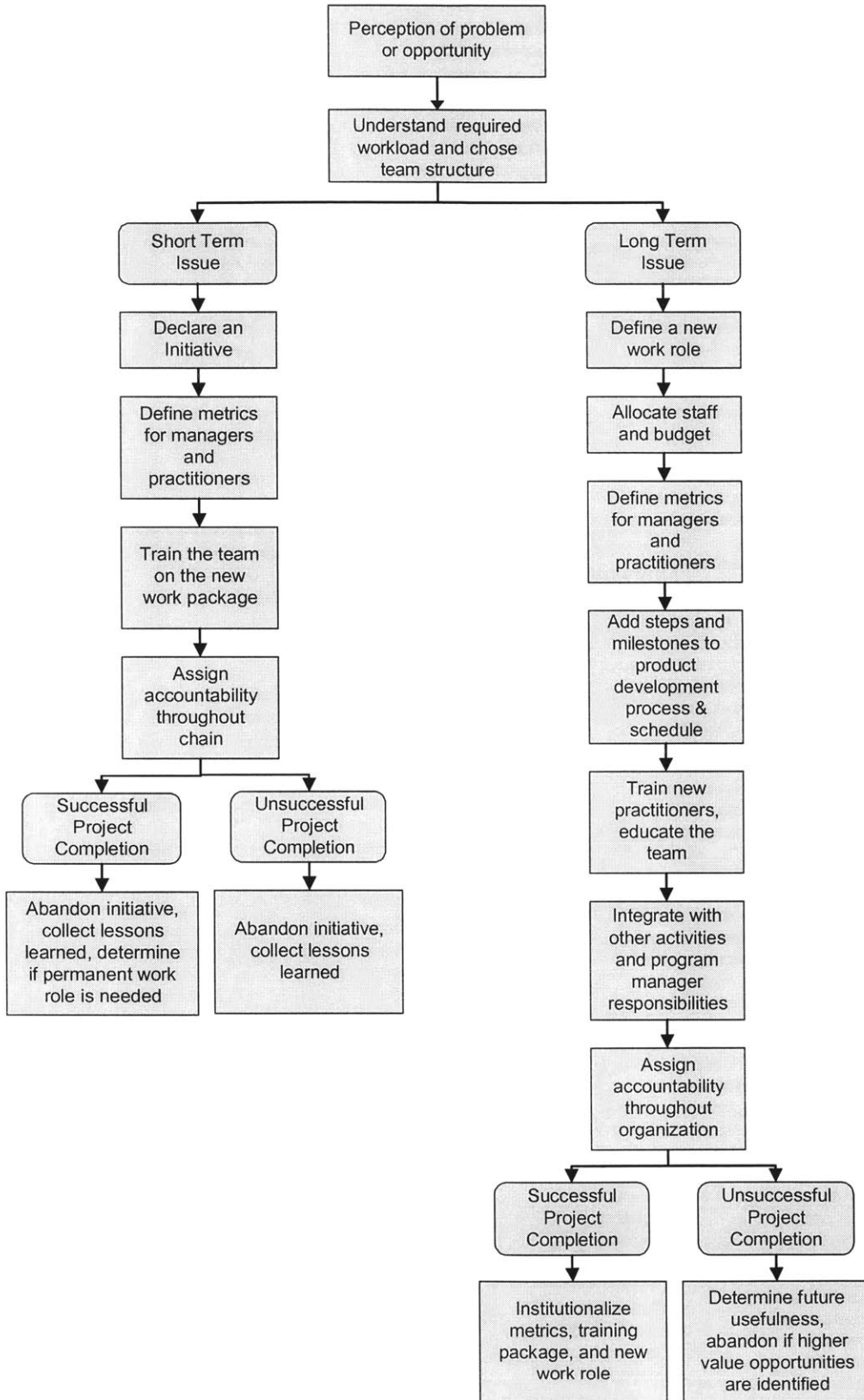


Figure 11: Suggested paths and processes for introduction of new work packages

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## **Chapter 8: Lessons in Processes**

Processes rather than tools are what make VRM beneficial. Tools such as 3DCS can give unquestionable benefit, but the understanding of and adherence to logical VRM processes will better target those tools for maximum effect. Books from Whitney (2004) and Thornton (2003) define excellent VRM processes, and six-sigma books such as Yang (2003) define additional analysis processes useful in VRM activities, but the processes to maximize the effect those VRM processes have on the product have received little focus.

The absence of well defined processes connecting data collection, VRM, and engineering will serve to sub-optimize these small pieces rather than optimize the whole product. Focus needs to be placed on the forest rather than the trees, and the three biggest returns on investment will be to improve the data collection process, the communication process, and the integration process.

### **8.1 Data Collection Process**

The processes used to collect data are, like the processes for gathering requirements and objectives, the basis upon which all other activities are built. Important aspects to consider are cost accounting and ownership, and data integrity.

#### **8.1.1 Cost accounting and ownership**

As mentioned in Chapter 2.1.3, internal and external suppliers are often asked to take measurements in the factory without an understanding of how these actions will affect the product, or why the measurements are being taken. Furthermore, it is rare that the additional time and cost of taking the measurements are removed from the cost accounting system, which will directly affect the metrics most factories are judged by: cost or cost-per-unit.

In order to avoid situations like Boeing faced in 1997 the measurements must provide immediate information to the factory for its own benefit in addition to the long term capability information. By giving production defined value for their actions at least one barrier to factory acceptance, the cost accounting barrier, can be dealt with head on.

Providing convincing financial incentives to the factory for a measurement plan can also give manufacturing a reason to feel ownership for the process. One of the many issues with Boeing's measurement plan was that manufacturing was handed a measurement plan and ordered to fulfill its requirements. There was no sense of ownership within the factory for the quality of the results, any follow-on analysis or communication, or any improvements to the measurements or measurement processes. If production feels they are getting a return on their measurement investment, they will take actions to maximize that return. That willingness to act for the betterment of the process is the "sense of ownership" required to ensure measurements will be taken, taken well, and used to the benefit of the product.

### **8.1.2 Data Integrity**

Data integrity is defined as ensuring the data reflects the actual value involved, contains sufficient detail, is posted in a timely manner, stored securely, readily retrievable, and is safeguarded against improper alteration, disclosure, or use (U.C. Berkeley 2004).

These seemingly basic and obvious rules are fundamentals that are often overlooked. If the data at the beginning of the development process does not conform to these aspects in any way, no amount of data integrity later will undo the "garbage in – garbage out" realities of information management.

Two of the most overlooked parts of this definition are sufficient detail, and readily retrievable. All types of data management systems must walk a fine line between too little information to be useful and too much for an engineer to effectively or efficiently find the pertinent information. When there are several production facilities or suppliers

there is often a proliferation of data locations or even software used to search the data. If engineers looking for process capability data must first determine which system to look in, then determine how to use the particular facility's search capabilities, only then to discover if the needed data exists, then it will not be long until engineering limits their willingness to search for the data.

At this point not only is the rest of the development process sub-optimized and potentially corrupt, but production may begin to feel the data they collect for engineering is unused and no longer worth taking. This problem and its results have been previously discussed.

## **8.2 Communication Process**

In multi-department companies effective communication is crucial for timely and accurate transfer of data and ideas. Management has a responsibility and the ability to maximize the effectiveness of communication within the product development process.

First and foremost is to define the proper communication mediums and procedure. This can be as simple as ensuring people are educated in how to access the system of record for various information. This is especially important as new data systems are brought on-line that might not otherwise be brought to the attention of all the groups in the company.

Part of defining the proper communication mediums is simplicity. In large companies and companies that work with multiple suppliers, there are often different standards of communication between different locations or between internal groups and external companies. Having one standard of communication that is used both internally and externally will simplify the communication process, quicken the learning curve thereby increasing information accuracy and understandability, and generally make the daily tasks of engineering easier to manage.

Beyond electronic communication, personal communication effectiveness can have a large impact on the quality or quantity of information transfer. Experts in various fields often present data or information in a format that is only readily understandable by another expert, and not by the actual audience for the information. An often used example is the chart of O-ring temperatures that contained the proper information but failed to prevent NASA from launching the Challenger space shuttle in 1986 (Tufte 1997). Basic training in presentation effectiveness and communication principles might not have prevented this tragedy, and might not prevent other failures in information transfer, but the risk of not training people to communicate far outweigh the costs of training.

### **8.3 Integration Process**

If there is a risk the data management and communication processes in between the data collection, VRM, and engineering processes can get overlooked, then businesses should look at ways to mitigate this risk. Three important integration efforts are physical integration, team integration, and supplier integration.

#### **8.3.1 Physical Integration**

Distance matters, and all efforts to co-locate the separate teams should be taken. Co-location carries two important benefits in the informal “water cooler” interactions that can occur and in individuals’ willingness to trust and cooperate with team members.

“Water cooler” interactions are those informal meetings of co-workers, frequently around the water cooler or the coffee pot, where the happenstance meeting induces a conversation where important information is exchanged. Examples of “water cooler” interactions that lead to breakthroughs include an interaction between two teams at 3M – one responsible for sandpaper and one for adhesives – that lead to the invention of masking tape (Eisenhart 2000).

Bradner and Mark (2002) also investigated the effect of distance on trust and cooperation within teams. Despite the seemingly insignificant difference between a team spread across a state and one across the world, they found that distance or perceived distance had a significant impact on individuals' tendency to trust information from, cooperate with, or attempt to deceive those at a distance. This type of behavior can help explain the ineffectiveness of VRM efforts that are conducted in different locations – even floors within the same building – than the engineering activities.

While research is being done into the creation of “virtual water coolers” and methods for decreasing the negative effects of distance on office interaction, it is clear the easiest solution is to decrease distance and increase the interaction of the various teams responsible for the overall design of the product. It is also clear that infinite improvement in VRM-specific processes or information quality will have no effect on overcoming these important realities of human interaction.

### **8.3.2 Team Integration**

An important trend in product development is “concurrent engineering,” or “integrated product process development.” These are management techniques that simultaneously integrate all essential product development activities through the use of multi-disciplinary teams to optimize design, manufacturing and supportability processes. By integrating production specialists, VRM specialists, and engineering specialists, several of the communication barriers can be broken down and information can flow more freely.

Fine (1998) extends this idea beyond the engineering processes into supply chain and business processes, proposing the tighter all business functions are bound together the faster the responsiveness of the company and the better equipped a company will be to optimize the whole rather than sub-optimize each piece of the product lifecycle. This principle holds true for VRM processes and people.

By integrating VRM into production and engineering teams, whether it be through a blended team structure discussed in Chapter 7 or through other mechanisms and structures, VRM will have to rely less on formal communication processes and be positioned to more effectively respond to the needs of the product.

### **8.3.3 Supplier Integration**

When co-developing a product with a supplier, companies can rarely define or control the processes suppliers use to develop or manufacture their components. They therefore must manage suppliers by fully and accurately defining requirements and objectives in advance of both development and then production. Including supplier representatives on an integrated product development team is a great integration step, but suppliers must be managed based on performance to exact requirements contained in contractual agreements.

Boeing has in the past attempted different methods for supplier process management, varying from no interaction to forcing processes upon the suppliers. Opinions vary on the success of Boeing intervention, but more than not the thought is that involvement costs a great deal of money and provides little if any benefit. The most critical view is that Boeing hired experts to do a job better or cheaper than Boeing could, but then tries to make the supplier follow the processes Boeing would if it were done internally, driving cost up or quality down.

Even if one believes helping suppliers with VRM is worthwhile, the staffing reality for most companies is that they do not have spare VRM experts. Existing experts need to concentrate their knowledge on internal issues rather than external details.

With no one to manage or aid suppliers and partners in VRM techniques, it would be dangerous to force VRM on them and trust it will be done properly. Instead, vital resources need to concentrate on providing suppliers and partners with clear and accurate

requirements, KCs, tolerances, and Cpk's for suppliers to work to. This is the only viable option to “manage” supplier efforts.

#### **8.4 What to learn**

The absence of well defined processes connecting data collection, VRM, and engineering will serve to sub-optimize these small pieces rather than optimize the whole product. By integrating the various development processes as tightly as possible, companies will realize more value from the overall development process.

Physical proximity as well as full development team membership will not only increase the communication of ideas and information, but will allow VRM to more quickly respond to emerging issues engineering faces, increasing VRM's value to the product and the company.

Lastly, because VRM affects the design of a product that is not currently in production, it often times has a very long payback period. By integrating it into the development process its value is going to be more apparent and definable before production begins, and is less likely to get phased out due to lack of results.

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## **Chapter 9: Conclusions**

The aim of this chapter is not to summarize the information contained in this thesis, but to synthesize the various case studies, lessons, and ideas to present a final look at VRM from a development process perspective. The hypothesis will be discussed to determine if there was enough data to support it, and some final thoughts on how to best improve an organization's VRM program will be considered.

The hypothesis of this paper is that processes and tools enable VRM success, but information, organization, and management structure are the main factors determining the degree of success a VRM program will experience.

### **9.1 Synthesis**

The first step in addressing the hypothesis is to look at the cargo floor case study, the lessons discussed in Chapters 5 through 8, and the second case study, dealing with the final aft body join of the 7E7, to determine how well they relate.

#### **9.1.1 “Case Study” – 7E7 Aft Final Body Join**

This section will quickly describe this case study. The details are intentionally left vague both for proprietary reasons and because the project's engineering purpose is not at issue. It is the effectiveness of VRM in the engineering development that is. However, for some frame of reference, it was determined a small description of the project was needed.

Every Boeing commercial aircraft since the 707 has a long cigar-shaped fuselage with a more or less conical nose, a body section through the majority of its length that remains constant in diameter (i.e. constant body section), and a taper at the tail. All current widebody aircraft are built in sections that resemble very large toilet paper rolls that are joined together to make the airplane one piece. Currently, these section joins are always

located in the constant body section, and never in the tapered tail section nor in the conical nose section.

When determining where to split the 7E7 into sections - and therefore where to have the section joins - it was decided to investigate putting the aft section join in the tapered area rather than at a constant body section area, for several engineering reasons. The Final Assembly and Delivery team was asked to determine if this type of join was manufacturable given certain cost and quality targets. A major component in determining an answer was to figure out if the new design would have an unfamiliar tolerance stack-up, or uncontrollable variation stack-up, and if so what this meant. In order to do this, FAD asked for a VRM analysis of the join, which was conducted over a roughly one month period.

The VRM methods followed the same “identification, assessment, mitigation” steps as the first case study. While the details of the steps are proprietary, they are mostly irrelevant. The only thing this paper is concerned with is the fact that the study found the tapered body join to induce significantly more variation than the constant body section join, and the effectiveness of the processes to get this information into the design of the product, which will be a major part of the discussion in the following subsection.

### **9.1.2 Case Study Support of the Lessons**

This section is going to walk through the lessons in information management, management and organizational support, and process in the order they appeared in this text. Rather than summarizing each section, it will attempt to draw out more detail from the case studies to provide “real world” examples in order to support, or make more resonant, the lessons.

Both case studies began with an investigation of the requirements. As a contractor to Boeing, direct access to the requirements database was not available. This made this task incredibly difficult. In itself this may seem a slight inconvenience, but in an era where

significant portions of design work are conducted by partners or contractors, lack of basic access to requirements by all those outside the corporate entity can be disastrous to the end product.

Identifying key characteristics was an interesting challenge for both case studies as well. While KCs are often clearly marked on part drawings, there are few if any assembly drawings that show assembly or system level KCs. While not a show-stopping problem, it clearly means that each new analysis must “reinvent the wheel” to determine what the assembly KCs are. It is good to reinvestigate the KCs from time-to-time, but the most common problem faced in the body-join analysis was my investigation of assembly KCs generated some that hadn’t been identified before. Unfortunately this invalidated the analysis in some peoples’ eyes, who simply responded that the analysis wasn’t even looking at the right KCs, and therefore couldn’t have been done properly. This reaction, while potentially understandable on an analysis of an existing product, was baffling on a new product that employed designs, materials, and concepts never before seen at the company. Nevertheless, it was an unforeseen challenge that reduced the effectiveness of VRM.

Process capability was an especially contentious subject. Entering into any conversation with engineering about process capability was an exercise in circular logic. The body join case study provides an excellent example. No process capability was available, since the process to join non-constant body section pieces existed. Engineering would not provide tolerances for the analysis in the stead of capability data, and would request the analysis be done using existing capability, even though it might not be precise. At the conclusion of the analysis, it was often stated that the results were worse than reality, because engineering would simply tighten the tolerance to bring the variation back under control.

The spiral would continue when engineering was again asked for tolerance values they intended to specify, based on the analysis. This was to determine both the implications of the tolerance in the analysis and to determine if that capability could be achieved.

Multiple times a value was finally given, only to have operations and manufacturing determine that tolerance was impossible to attain, at which point engineering individuals would reply that manufacturing just didn't want to do anything hard, and dismiss their concerns.

Clearly, the lack of credible data at the beginning of the process hindered the effectiveness of the results. The fact that the analysis was not performed under the watching eye of engineering, but instead only shown at completion – so as not to distract from the “real” engineering work – also served to inject doubt into the process. After all, who from engineering can say the analysis was done properly and the results should be heeded if no one from engineering knows how the analysis was done?

To top all this off, no metric existed to judge the effectiveness of VRM activity or the amount of VRM output engineering incorporated into the design. The only accountability development teams had to VRM was their own sense of right and wrong and what is best for the product. This rarely works in the favor of VRM when it is the development teams' designs VRM seeks to change. Most of the arguments used in the body join case study involved financial, quality, and time aspects, but in the end it was usually a personal appeal to the engineer's sense of duty to the product that affected behavior, not raw numbers or data. While noble, this is a process that clearly relies on a safety net of conscience rather than effective practices, and if too many items hit the safety net some are going to start falling through.

The last example this section will discuss is one of effective communication. Explicitly this thesis spoke of communicating data and ideas, but there is much more to communication than this. The entire premise of the body join analysis was a design decision to put the aft join in a tapered section of the fuselage. Over one man-month of work went into the analysis, and when it came time to present, instead of presenting the findings the VRM team was told the design decision had been reversed less than a week after it had been made. No one was told of the reversal because the group that wanted to make the change made a miscalculation in their case to have a tapered section join, and to

avoid embarrassing them, the design was changed back to a constant body section join with no announcement. Apparently no thought went into the loss of time and work associated with not informing VRM, and who knows how many other groups, about the design change. While one man-month may seem insignificant on a project of the scale of the 7E7, this wasn't the only project this type of thing can happen to, and it wasn't the only time. Cost and quality will in one way or another suffer because of a lack of formal communication protocol in situations like this.

## **9.2 Was the Problem “Solved”**

As stated in Chapter 3.4, firm data on the effect of VRM, and more specifically the case studies and whitepaper, on the 7E7 are unattainable at this time. Because of this, subjective measures were developed to determine the success of the projects. Those measures were:

- Are ASIT members convinced that focusing attention and/or improvement activities on identified processes will contribute to improved VRM performance versus previous VRM efforts
- Is awareness throughout the management structure heightened with respect to VRM issues, and is management convinced identified processes and improvement efforts are valid and will contribute to improved product performance versus previous product development efforts
- Are the conclusions valid across other types of analysis, work efforts, or business needs
- Were the topics, improvement suggestions, and conclusions in accordance with experience and results from one or both of the case studies

In one-on-one and group meetings with the ASIT team it became clear that the whitepaper work was well received. During writing and after release of the whitepaper the interview notes, drafts, and final copy were used and referenced often. Once released and disseminated throughout the engineering management structure, several email

responses showed up discussing favorable opinions of the paper, both its content and style. Two responses in particular stated that the words VRM could be removed and any other initiative put in its place, and the paper would still be relevant and correct. Finally, Chapter 9.1.2 was written to detail the strong correlation between both case studies and the material contained in this thesis.

While there is room for interpretation and argument, it seems that the work contained in this thesis supported the hypothesis, and at least pointed a clear path to “solving” long-term problems with Boeing’s VRM program.

### **9.3 See the Forest, Focus on the Trees**

A key tenet of VRM is that it is critical to determine where the weakest or most vulnerable link in the product is and focus attention and energy there. This same philosophy should be used to determine the weakest link in the development chain and focus attention there until it is strong. At this point the new tools, processes, or work roles should be institutionalized and improvement efforts refocused on whatever the new weakest link is.

Short of this holistic development process view, each link will be sub-optimized, their benefits compartmentalized, and the product weakened from either a cost, quality, or functionality standpoint. By looking at the whole forest, the weakest trees can be tended to and given the attention they need, thereby improving the health of the whole forest.

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## Appendix 1: Whitepaper Interviewee List

The following people contributed ideas and experience to the creation of this document

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	Ray Smith	Wichita, KS
	Scott Smith	Wichita, KS
	Lisa Spoon	Wichita, KS
	Bret Stucki	Renton, WA
	Anna Thornton	External
	Steve Walls	Everett, WA
	Bruce Wilson	St. Louis, MO
	Monte Wright	Seattle, WA

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## Appendix 2: Interview Questions

- A. What was the design team structure?
  - (IPT?, who involved, who left out? Suppliers?)
  - What were the member titles and responsibilities?
- B. How did requirements enter the project – as raw customer requirements or as technical requirements already scrubbed from customer requirements?
  - Would you have like requirements in some other form, and if so what form and why?
- C. What other methods or inputs were used (to determine KCs)?
  - (reqt's docs, FMEA, warranty data, past customer complaints, quality reports, supplier info/team members, process experts/reports)
- D. What phases and gates (or other process definition) did the design process follow once requirements were received?
  - How were decisions made, in what order, ...?
- E. (Assuming I'm talking to people who used DM in some form) What were your reasons / goals for using DM?
  - (looking for something around best design at lower cost using right tolerance, ensuring minimal defects. Anything else may indicate they don't understand the point of DM)
  - (Hopefully get how it applies both to the product and the design process)
- F. What were the specific DM tasks and how did they fit into the above (phase and gate question) process?
  - (every day attention, once a week/month conversation)
  - (In each meeting, on team member's own time, report outs or no)
  - (part of the process or it's own side process)
  - [In conjunction with above questions can compare intent to execution]
- G. What tools were available to execute the above tasks, and who had access to them?
- H. Who executed and who was ultimately responsible for DM?
  - Were there VRM "experts" on the team, or was VRM everyone's responsibility?
    - If experts, how much authority did they have, and was it enough/too much?
- I. What metrics were used to define / track DM effort?
- J. Were the engineers compensated/rated based on the above metrics?
  - If so, in you opinion was the compensation enough to drive the proper behavior?
  - If not, what metrics were they compensated on?
- K. Now that I have a view of the engineers work and incentive, how well did the incoming requirements and other inputs mentioned above allow engineers to do and complete work, especially around DM efforts?
  - What other inputs would have helped the team and how?
- L. How was the DM effort scoped?
  - (What was the initial CR level of abstraction used?)
  - (How were systems and subsystems grouped/defined to aid in the process?)

- (How were requirements to keep in the DM effort extracted or cast aside?)
  - (How were the KCs accepted / rejected / ignored? – process for decisions)
  - To what level of detail do you model? (looking for some type of answer that will lead me to believe they are “way too much” “way too little” or right at 80-20) (model documentation would be awesome)
  - If the cost of addressing a System KC is/was unknown, how did the team decide which ones to address? (non-value quantification, gut feel, investigation, what process?)
  - How was variation predicted
    - Was EXPECTED or BEST CASE variation used?
  - How were flowdowns validated
  - In addressing costs, did the team use qualitative, step, or continuous cost functions? Why?
  - How accurate did the models turn out to be?
  - (How far down into “rat-holes” did the group go? How long did it take the group to realize they were in a rat hole? What was the process for getting out? How do you think the team would rank on keeping focus / scope in mind? Why, and how could it have been better?)
  - Did /How often did poorly defined KCs introduce extensive discussion or anger? How much “rework” time usually resulted from such “misunderstandings?”
  - If a chosen mitigation strategy became a schedule bottleneck, which came first – schedule or mitigation? Why? Any exceptions?
    - What happened as a result when production started?
    - How do you think this effected the customer experience/satisfaction?
- M. When designing, how much focus was put on using in-process tuning, ensuring optimal assembly process, proper indexing and datuming, proper tolerances?
- N. Determinite assembly or fixtured assembly? Why and what was the decision process?
- O. How much thought or effort went into error proofing designs for assembly? Can you give an example?
- P. How were KCs communicated to suppliers? Did the suppliers understand which KCs to produce to and which were just “comments?” If not, what were the approximate costs in terms of money and time lost?
  - How is VRM applied at / forced on suppliers? What do you feel are the cost / benefit tradeoffs of moving from this method (or are you at the best method)?
- Q. After production, were field incidents reported back to the team? If so how, and what process was used to deal with the information, if not, why not?
  - If field incidents were reported back, do you have any data on the effectiveness of VRM efforts to reduce the number of incidents? If no data, gut feel?
- R. How were the VRM process, results, and lessons learned documented and shared?
- S. Which comes first – performance, quality, cost?

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