Evaluation and Assessment of Variation Risk Management and the Supporting Tools and Techniques

by

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Bachelor of Science
Texas A&M University, 1996

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE DEGREE OF

MASTERS OF SCIENCE
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 1998
[June 1998]

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Submitted to the Department of Mechanical Engineering
on May 22, 1998 in Partial Fulfillment of
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Abstract

All product development and production organizations suffer from variation in products or production processes. In the context of this thesis, variation is the deviation from nominal design values or operational specifications. Due to an inability to control all variation, a subset of these parameters is generally isolated for special attention. They are commonly referred to as Key Characteristic (KCs). This subset of parameters is selected and prioritized based on the probability of parameter variation and the cost associated with variation. Research has revealed that any variation from the nominal design value or operational specification of these KC's can have a significant, negative impact on cost, performance and quality of products.

Most companies have realized that risk associated with KC variation must be managed. This realization has led to development of specialized methodologies. Through a series of company assessments on variation risk management (VRM) processes, it has been possible to identify a number of best practices and problem areas. The author has used these assessment results to develop a VRM guideline. This Guideline recommends a sequence of procedures that must be performed to support VRM from an integrated product perspective. To support implementation of VRM, supporting tools and techniques have also been evaluated and aligned with the defined VRM procedures.

Thesis Supervisor: Anna Thornton
Title: Associate Professor of Mechanical Engineering

Acknowledgments

First and foremost, I'd like to thank to Dr. Anna Thornton for all of her guidance and patience during my research. In addition to being a great research advisor, Dr. Thornton became a friend who made even the most challenging parts of my research an enjoyable learning experience.

I would like to thank Dr. Warren Seering and the Center for Innovation in Product Development, for the research funding and the guidance to get my research started.

I would like to thank Boeing Commercial Aircraft Group, Ford Motor Company and the Xerox Corporation for providing inputs and supporting information for this thesis. A special thanks goes to the many individuals that served as a contact to these companies.

I would also like to thank Mark Ardayfio, Basak Ertan and Susan Travis for providing the support and motivation to help keep my research on track.

I also want to thank my family for their continued support and encouragement through these challenging years. A very special thanks goes my brother Tom for his endless support.

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Abbreviations

AE	Application Engineers
AIAQ	Automotive Industry Action Group
ANOVA	Analysis of Variation
APQP	Advanced Product Quality Planning and Control Plan
AQS	Advanced Quality Systems
AVT	Advanced Vehicle Technology
CAD	Computer Aided Drafting
CAE	Computer Aided Engineering
CAM	Computer Aided Drafting
CC	Critical Characteristic
CDVR	Customer Driven Vehicle Reports
CFT	Cross Functional Teams
CP	Critical Parameter
CP	Critical Parameter
Cp	Process Potential
CPD	Critical Parameter Development
CPI	Critical Parameter Implementation
Cpk	Process Performance
CPM	Critical Parameter Management
CS	Critical Specification
CSI	Continuous Supplier Involvement
DCP	Dynamic Control Plan
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMEA	Design Failure Modes and Effects Analysis
DOE	Design of Experiments
DVA	Dimensional Variation Analysis
FAST	Functional Analysis System Technique
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FPS	Ford Production System
HIC	High Impact Characteristic
HLM	High-Medium-Low

HoQ	House of Quality
HVC	Hardware Variability Control
IOC	Input/Output/Constraint
KC	Key Characteristics
LAL	Lower Allowable Limit
MFG	Manufacturing
MIT	Massachusetts Institute of Technology
MSA	Measurement Systems Analysis
PCD	Process Control Document
PDE	Product Development Environment
PDS	Product Development Space
PFMEA	Process Failure Modes and Effects Analysis
PPAP	Production Part Approval Plan
QC	Quality Control
QFD	Quality Functional Deployment
QS-9000	Quality System Requirements
RPN	Risk Priority Number
RPP	Risk Priority Number
RSS	Root Sum Square
SC	Significant Characteristic
SCD	Specification Control Document
SPC	Statistical Process Control
TTM	Time to Market
TVDCD	Total Vehicle Dimensional Control Discipline
UAL	Upper Allowable Limit
VRM	Variation Risk Management
VSA	Variability Simulation Analysis

1 Introduction to Variation Risk Management and the Research

1.1 General Introduction

All product development and production organizations suffer from variation in product or production process parameters. In the context of this thesis, variation is deviation from nominal design values or operational specifications. Due to an inability to control all variation, a subset of these parameters is generally isolated for special attention. They are commonly referred to as Key Characteristic[1] (KCs) or Critical Parameters (CPs). This subset of parameters is selected and prioritized based on probability of parameter variation and costs associated with this variation. Research has revealed that any variation from nominal design values or operational specification of these KC's can have a significant, negative impact on cost, performance and quality of the product [Lee and Thornton 1997].

Most companies have realized that risk associated with KC variation must be managed. This realization has led to development of specialized methodologies. Key Characteristic Methods, Critical Parameter Management, 6 Sigma Design, Hardware Variability Control, Advanced Quality Systems, Variation Control and Dimensional Management are several examples. Their common objective is to provide some level of Variation Risk Management (VRM). The process of VRM involves identification, assessment, mitigation, communication and documentation of variation sensitive parameters.

The Massachusetts Institute of Technology (MIT) Key Characteristic Research Group, directed by Dr. Anna Thornton, has conducted extensive research on VRM processes. This research has focused on advancing VRM processes based on identified needs of multiple industries. In conjunction with their research, two annual Key Characteristic Symposia have been hosted. During these two events numerous industries presented their successes and failures with their own KC management processes. Open forum discussions and working groups were used to establish a set of industry needs that will guide continued research. This compiled set addressed

[1] Key Characteristics will be used as a general name for the subset of variation sensitive parameters to be controlled.

current barriers and future improvements needed for a more effective VRM process. It was evident from both discussions and identified needs that most companies have not achieved complete[2] VRM integration. Considered a desired approach by most companies, a complete VRM process is viewed as a solution to many of the identified problems.

In addition to KC symposia, research information for the KC Group was obtained through benchmarking VRM activities at more than 30 companies. These benchmarking activities resulted in development of a MIT Key Characteristics Maturity Model (see Appendix C). This model contains 22 elements identified as being vital to effective execution of VRM while explicit performance requirements define four levels of maturity for each element. The MIT KC Group and several companies have used this model to evaluate their current state of application and identify areas in need of improvement. These assessments have revealed that most companies are generally mature in only a few areas of VRM application.

While the need for better and more proactive Variation Risk Management techniques has become obvious to most companies, the best approach to manage this risk is not so clear. It has been noted that most VRM processes currently used are sufficient in some areas, but are clearly lacking in others. One particular assessment revealed that a company was good at KC identification, but ranked very low at considering cost tradeoffs during assessment and mitigation. Additionally, individual company assessments indicated that strengths and weaknesses between companies vary. In most situations, lack of complete VRM integration directly contributes to several identified process deficiencies. This lack of complete VRM integration has become the primary motivation for this thesis.

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[2] Complete is used to define a VRM process that supports use by all organizational functions, for all product levels during all product development phases in an integrated and complete manner. Optimization is applied to overall application of VRM as well as individual VRM stages and/or procedures.

The author has hypothesized, based on preliminary research, that discontinuities[3] exist in most currently used VRM processes. These discontinuities are believed to be the result of VRM implementation activities that have focused only on specific problem areas while overlooking the complete VRM application. This has led to implementation of a partial VRM process and use of poorly aligned tools and techniques. The author believes that by identifying all VRM requirements and establishing a method to identify discontinuities, existing processes can be assessed for supporting practices and problem areas. By combining identified VRM process requirements, supporting practices and identified tools and techniques, a VRM Guideline is developed. The Guideline includes a model VRM process (sequence of procedures[4]) and a recommended set of tools and techniques that can support it.

Presentation of this thesis follows the order in which the VRM guideline is developed. The remainder if this chapter will provide an overview of variation risk management and research supporting this thesis. Chapter two will focus defining VRM activities and requirements that will provide a baseline for company assessments. The following three chapters will discuss assessments for three primary companies. Chapter six will provide additional evaluation of identified tools and techniques that will be considered for the guideline. A tools and techniques section discusses advantages and disadvantages of identified supporting processes. The final chapter will present the proposed VRM guideline along with an overview of the defined procedures and recommended tools and techniques.

1.2 Overview of Variation Risk Management (VRM)

Variation Risk Management is the process of identifying, assessing and mitigating risk associated with variation sensitive product and process parameters. Variation of these parameters will negatively impact performance, production costs and/or customer satisfaction. This variation can be due to material properties, fabrication and assembly processes,

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[3] Discontinuities are viewed as breaks or segmentation in the VRM process that prevents integration from a complete company/process/product perspective. These discontinuities can result from implementation of processes that are focused at specific variation management areas without proper consideration for complete VRM integration.

[4] Sequence of procedures is the defined executable steps that make up the VRM guideline.

environmental conditions, and/or undesired noises that are inevitable to products and/or processes. Management of risk due to this variation involves application of these steps to systematically eliminate or minimize impacts of variation to the overall product. Step one is to *identify* potential KCs, sources of variation and their relationships throughout the product. Step two is to *assess* probability of variation occurring and cost resulting from expected variation; the combination of probability and cost will reflect KC risk. The final step is to *mitigate* risk through a collaborative selection of a risk mitigation alternative. All of these steps are supported through a continuous process of *documenting* VRM information and *communicating* it between organizational functions, Cross functional Teams (CFTs), and product developments.

Most companies have concluded that proper management of variation risk must be utilized to avoid costs associated with scrap or rework, low quality, product failures and customer dissatisfaction. Variation has been found to contribute to both recurring and non-recurring costs [Clausing 1994]. In addition to reducing unnecessary costs, companies advocate that VRM has helped reduce development cycle times, encourage coordination between design and manufacturing, coordinate measurement and inspection activities, and improve overall product quality.

The main emphasis of VRM is to minimize risk associated with variation sensitive parameters and to do it with cost-effective alternatives. Changing designs or production processes, reducing variation, controlling variation and inspecting out variation are all alternatives to mitigate expected risk. However, cost effectiveness and availability of each option changes throughout the product development process. On one hand, early development phases may involve more low-cost mitigation alternatives, but there is less available information that can quantify expected risk. On the other hand, later design phases are generally associated with fewer, high-cost options, but can provide more accurate information on expected KC risk. For example, in the early development stages it is cost effective to change designs or processes to eliminate or reduce sensitivity of parameters. However, effective use of this alternative depends on understanding the overall impact of variation to the product. This impact assessment requires design information that is not defined until later design phases. By the time details necessary for these assessments are defined, design or process changes may no longer be a cost-effective mitigation

alternative. Therefore, in order to make design changes to reduce variation impact it may be necessary to do so based on uncertain[5] information. This dilemma requires that VRM processes be capable of making cost and time driven tradeoffs based on uncertain information ensuring timely selection of cost-effective mitigation alternatives.

1.2.1 Advantages of using VRM

There are a number of advantages that can be gained through proper use of Variation Risk Management. In many cases VRM has helped to focus product development efforts on parameters that will have the greatest impact on overall designs. When early awareness is drawn to variation sensitive parameters, there is a high probability that these parameters will be addressed before designs make it to production. It is understood that greater benefits can be gained from designing out variation sensitivity as opposed to controlling it[Taguchi 1993]. Early resolution of these parameters will reduce late design changes. It will also increase the number of alternatives available to resolve problems caused by these parameters. Furthermore, identification and assessment functions serve as a check on robustness[6] of the design. Ensuring a robust design will help to improve overall product performance and produceability.

For VRM to be effective, it generally requires that potential KCs be assessed based on expected variation resulting from production processes. This VRM motivated assessment will require extensive interactions between design and manufacturing. Ensuring coordination between these two groups can result in higher manufacturing quality and lower production costs. Discussion between design and manufacturing will also help highlight poor design practices and target process improvement areas.

In addition, proper management of variation sensitive parameters will ensure that control and inspection plans are consistent with identified KCs for effective resource allocation. Mitigation activities determine which parameters must be incorporated in control and measurement plans.

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[5] Uncertain is use to describe information that is based on approximations, modeling, prototypes, historical data etc. that has been estimated based on the expected conditions and therefore will contain some inaccuracies.

[6] A robust design is one that is not sensitive to the experienced variation.

This step ensures that control and measurement plans are focused on identified problem areas and that corrective action measures are defined. It has been found that effective control and measurement plans will help to quickly resolve problems during production ramp activities [Leyland 1997]. As a result, VRM can help establish plans that will support production ramp and ensure effective management of variation risk throughout production.

The previous discussion has highlighted several reasons why VRM can be considered beneficial to a product development organization. In terms of cost control, VRM has been found to focus design efforts and to help encourage coordination between design and manufacturing. As for product quality, the process can help improve proper form, fit and function of finished products. In the area of customer satisfaction, VRM ensures special attention is given to any parameters that directly or indirectly impact customer requirements.

1.2.2 Stages of the VRM Process

The three primary stages of Variation Risk Management are identification, assessment, and mitigation of variation sensitive parameters. These stages can also be defined as the functions of the VRM process because they will perform specific actions on a set of inputs to generate desired outputs. The integration of these stages is supported through focused communication and documentation. A general representation of these stages has been presented in Figure 1.

Figure 1 illustrates the sequence of stages, interactions between organizational functions and general flow of information for the VRM process. The first stage is identification. It requires continuous review of product and process design information. The figure also indicates, with the dotted-line boxes, that identification is supported with inputs from various organizational functions. Once a potential KC is identified it is transferred to the assessment stage. Assessment is generally performed by a specific organizational function, but also requires inputs from other functions. Assessment will determine if KCs are valid or not valid. All valid KCs go on to the mitigation stage. Mitigation is a collaborative activity between multiple organizational functions. Alternatives selected during mitigation can result in design or process changes or in validated KCs to be controlled during production. Design and process changes require identification and assessment to be repeated. Controlled KCs require control plans and/or continuous improvement plans to be generated. All VRM stages must be properly executed and documented to ensure effective management of KCs. Each of the identified stages/functions is discussed in the following sections.

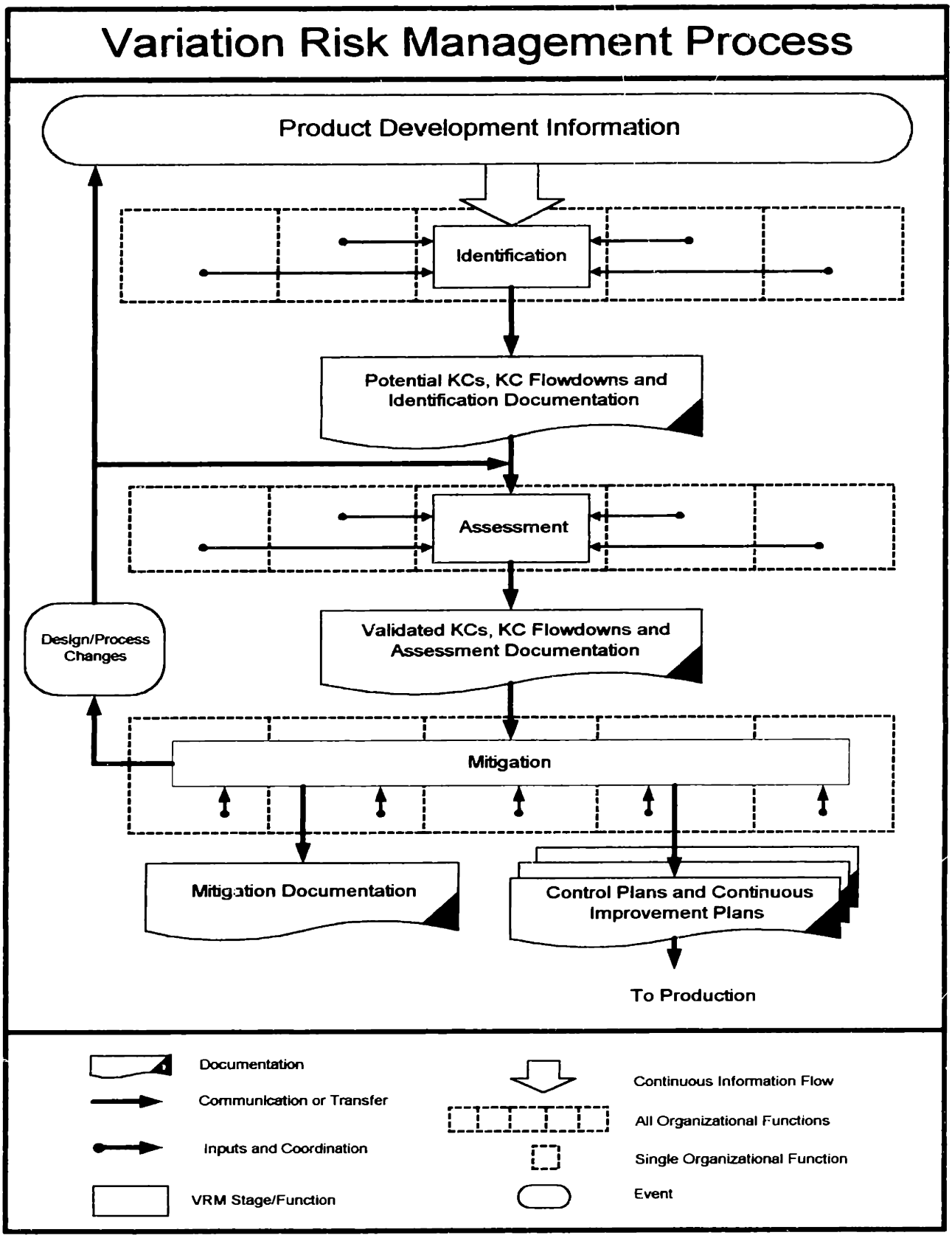


FIGURE 1: REPRESENTATION OF THE VRM PROCESS

1.2.2.1 Identification

Identification is used to select the set of potential KCs that will be considered during assessment and mitigation. It can be considered a continuous procedure used throughout all development phases to evaluate the overall product for potential KCs. While Design and Manufacturing Engineering generally perform identification activities, several additional organizational functions will participate in this activity. Established "definitions and methods" should be used to formalize what constitutes a potential KC and define areas of the product that must be considered. Lack of established "definitions and methods" can lead to incorrect identification and poor allocation of assessment and mitigation resources. It is also important that KCs are clearly defined to ensure resource allocation based on probability and cost of variation. A common mistake of VRM identification is to select parameters that are important to design, but are not sensitive to expected variation.

The fundamentals of KC identification stem from losses caused by the inability to maintain nominal design specifications during production. The Taguchi Loss Function Concept (see Figure 2) is a model that represents this concept. This concept suggests that any variation from nominal values of certain parameters will result in some loss to the product [Fowlkes and Creveling 1995]. This loss increases as the parameter value moves further away from nominal. Additionally, this loss begins to occur well before lower allowable limits (LAL) and upper allowable limits (UAL) are reached. As sensitivity of parameters increase, total-loss curves will become steeper. When used as a criterion, the loss function encourages identification of sensitive parameters. All parameters with steep loss functions will require special consideration and control to reduce loss due to variation.

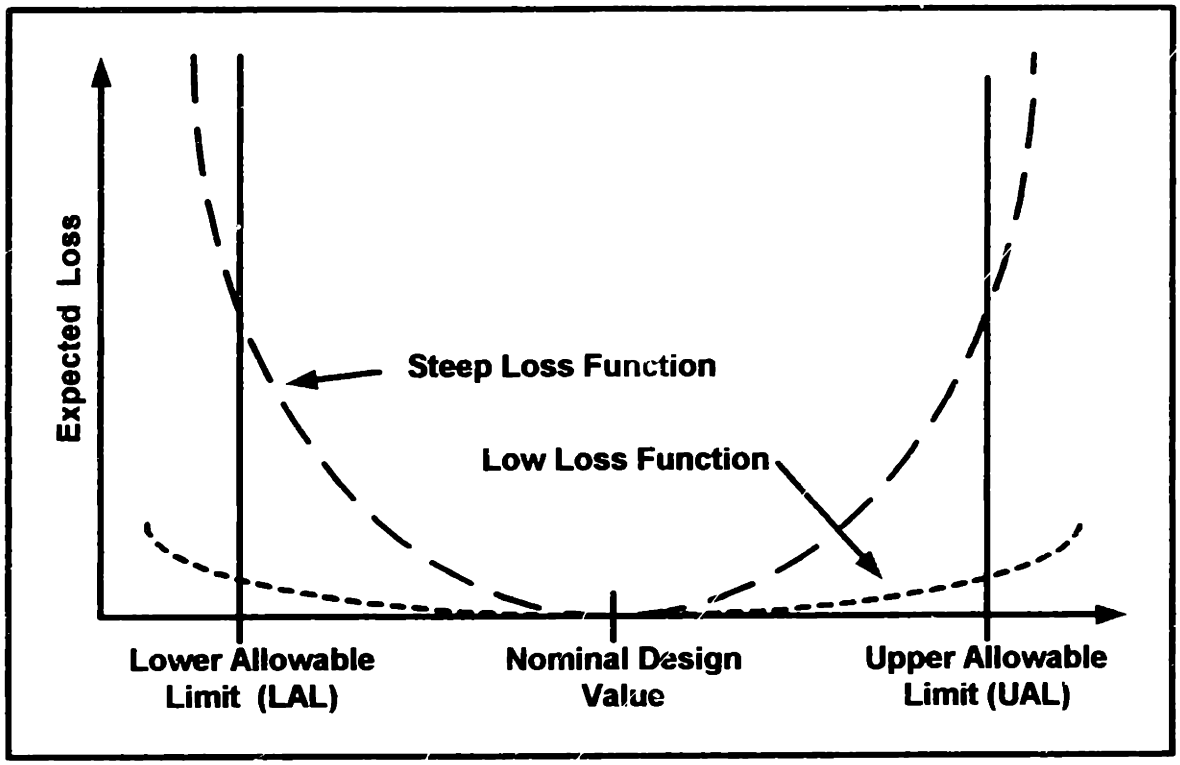


FIGURE 2: ILLUSTRATION OF THE COST/ LOSS FUNCTION CONCEPT

Identification should be motivated by and linked to high-level product and customer requirements. A KC flowdown process is generally used to trace overall customer and product requirements to lower parameters where variation may originate or can be assessed and mitigated. KC flowdown is the process of identifying relationships and interactions between product-level and feature-level KCs. Processes such as Extended Quality Functional Deployment, Drawing and Build Trees and Functional Diagrams are often used as KC flowdown tools. The flowdown process will result in a KC Tree. Figure 3 shows an example of a KC flowdown of the contour and drag requirements for a horizontal stabilizer wing [Lee and Thornton 1997]. This KC Tree visually illustrates relationships of KCs between product-level requirements and feature-level parameters. Whatever method is used to perform KC flowdowns, it is important to maintain traceability of KC information.

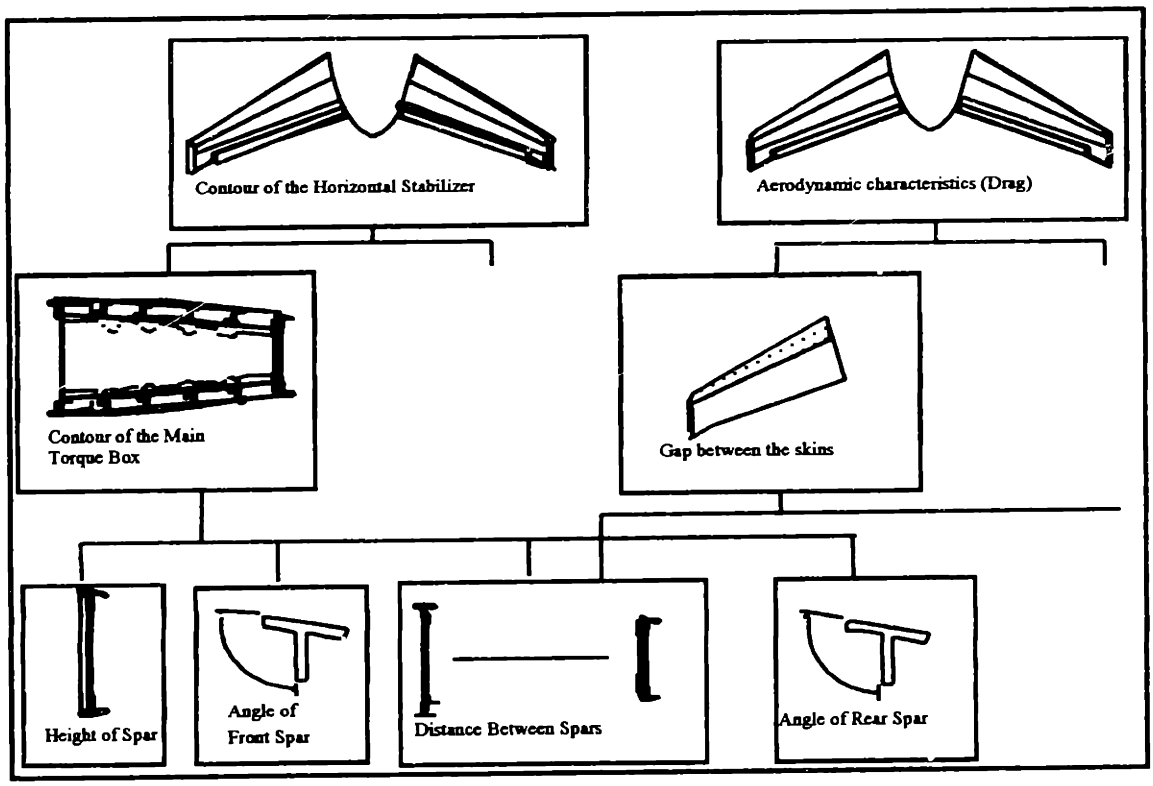


FIGURE 3: ILLUSTRATION OF A KC TREE FORMED DURING THE FLOWDOWN PROCESS

The identification function must also review products for KCs that do not originate from high-level requirements. It is very common for KCs to be identified at intermediate or lower-levels of the product as more information is determined during the product development process. For example, during design and manufacturing process selection it was realized that the angle of the rear spar (see Figure 3) was to experience sufficient variation. This in turn leads to identification of a potential KC. To determine the higher-level impact, a KC flowup will provide necessary information indicating parameters that can impact contour and drag. In other situations it will be necessary to consider both flowdown and flowup of potential KCs to identify sources and/or impacts of variation. The flowdown will reveal the source of variation necessary for accurate assessments. In terms of the example, a flowdown may identify a material property or process parameter that must be controlled to ensure proper angle of the rear spar. If traceability can be established between the sources of variation and higher-level impact area, assessment and mitigation will be easier to perform and reactive measures will be more accurate.

New technology[7] must also be considered as a potential source of KCs. It is preferable to identify potential KCs during development stages of technology. Early identification will ensure that the problem is resolved before the technology is implemented or addressed during product implementation.

1.2.2.2 Assessment

The assessment stage is used to determine expected cost resulting from variation and probability that undesired parameter variation occurs. Assessment results will help determine if an identified potential KC should be validated for mitigation. Not all identified potential KCs need to be validated. This is generally the case for low-cost/low-probability parameters, with exception for some safety and legal parameters, which are generally not validated for mitigation. For high-cost/low-probability and low-cost/high-probability parameters, assessment must be used to determine if they are validated. KCs that fall into high-cost/high-probability category will almost always be validated for mitigation. The assessment function must be able to distinguish which identified potential KCs actually require mitigation versus those that do not justify allocation of mitigation resources. Upon completion of assessment, all supporting information must be passed on to support mitigation.

		Probability of Variation Impact	
		Low	*High*
Cost of Variation	*low*	***Not a Valid KC***	***Assessment Required To Validate***
	high	***Assessment Required To Validate***	***Valid KC***

Table 1: KC Validation based on Cost and Probability of Variation Impact

[7] New Technology is used to address technologies that have not been tested and validated in the product application.

Availability of information often impacts timing and accuracy of assessment activities. This results from the typical sequence in which specific design details are determined as development proceeds or product designs are finalized. As reflected by the discussion on KC flowdown processes, variation can often be traced to lower-level parameters. In many situations details that define lower-level parameters may not be known until detail design or later development phases. Obtaining information at an earlier phase will have an added cost and higher level of uncertainty. If assessment is performed without sufficient information there is a risk of overlooking a valid KC and/or validating a non-valid KC. An overlooked KC may result in late design changes or problems in production. And selected non-valid KC can result in wasted mitigation resources, unnecessary design/process changes, and/or wasted inspection/control measures. However, if assessment is delayed to wait for better information, the number of cost-effective mitigation alternatives will be reduced. As a result, the assessment function must balance the risk and cost for early completion with delayed assessments.

Most assessments are based on information that is either qualitative or quantitative. Qualitative assessments are generally based on individual knowledge or experience that can have a high level of uncertainty. Quantitative assessments commonly involve use of modeling, prototypes, engineering analysis and specific design information that has less uncertainty. Qualitative data is generally easier to obtain, but does not provide the level of accuracy required for sound assessments. The type of information that is best for a specific assessment will vary, but a general rule is that quantitative assessments will provide more accurate results leading to a more effective mitigation. For example, with the horizontal stabilizer wing (see Figure 3) a qualitative assessment may indicate that the gap between skins is cause of undesired variation because it is obvious and known from experience. A quantitative analysis would trace drag specifically to potential causes of variation, which in this example includes both skin gap and distance between spars. Although some qualitative assessments may have identified the distance between the spars as a potential problem, there may not have been sufficient understanding to determine how it was contributing to the problem or if it should be classified as a KC. It is understood that insufficient quantitative information will make it difficult to quantify product performance, function or form vital to effectively assess variation risk [Lee and Thornton 1996a]. The

disadvantage of quantitative information is that it is usually less available and often requires more resources to obtain. Tools and techniques selected to support assessment must support use of both types of information.

1.2.2.3 Mitigation

Mitigation involves selecting cost-effective alternatives to minimize risk imposed by sensitive parameters and expected variation. As stated in the previous discussion, this selection process must be based on information determined during assessment. Assessment information will indicate the risk and costs associated with KCs and establish a basis to make necessary tradeoffs. Many of these tradeoffs will be made between design and production processes. A collaborative decision on each alternative should be reached between all impacted organizational functions. This can be achieved through the use of Cross Functional Teams (CFTs) and/or interaction and coordination between organizational functions. CFTs have been found to be a key factor for integrating design and manufacturing groups [Wheelwright and Clark 1995]. In most applications, CFTs will provide sufficient integration for collaborative decisions on mitigation alternatives.

Timing of mitigation will impact the cost and availability of mitigation alternatives. As with the assessment function, mitigation should be completed as early in the development as possible. Mitigation can be achieved by changing the design or production processes, improving the process, controlling the variation or inspecting-out[8] the problem areas. In the early development phases, all of these options are generally available at their lowest overall cost of application. As the development proceeds, each of the alternatives can be eliminated (generally in the listed order) or become less cost-effective to implement. The electronic industry estimates that the cost for correcting a design flaw during early stages of a major electronics product might be around $1,000. A mistake that is not discovered until final production stages may cost over $10 million [Himmelfarb, 1992]. Because mitigation must be a collaborative decision and it is desirable to

[8] Inspecting out has been defined here as the process of identifying faulty items and removing them from the acceptable parts; this approach generally includes the scrap or rework of faulty parts.

complete it in early development phases, it is essential to initiate and maintain interaction between organizational functions as soon as the development starts.

Mitigation requires accurate and updated information to ensure effective consideration of all possible alternatives. Cost of applying an alternative, ease of implementation, effectiveness of implementation and impacts to the overall product are examples of information that should be available. This information can be obtained from assessment activities, CFTs, organizational functions, mitigation studies, historical data and other sources. This need for sufficient information during VRM activities requires communication and documentation procedures to be established and enforced through all VRM stages.

1.2.2.4 Communication and Documentation

Communication and documentation functions support information exchange required for identification, assessment and mitigation. Communication includes all measures used to exchange information required for the VRM process. This can include transfer of information between organizational functions, product development phases and other developments. Documentation can be viewed as having two functions. The first is in the form of instructions for VRM. The second establishes a framework for recording all VRM information. These functions ensure that VRM is performed correctly, information is interpreted consistently and results are continually available for use/reuse. Both the communication and documentation functions have a great deal of interdependence and have been addressed together for this reason. The combination of these two functions will be referred to as VRM information exchange.

In most cases information exchange will be an integrated part of the primary VRM functions because of the need to effectively manage and continually access information related to KCs. In other cases communication and documentation may be supported through information management activities for the product development process. In either case, successful implementation of the VRM process depends on an integrated approach to manage information for identification, assessment and mitigation functions. Intensive communication supported through a clearly defined process is a key enabler to an integrated problem solving approach

[Wheelwright and Clark 1992]. Measures must be put in place to ensure that VRM documentation and communication procedures are clearly established.

Proper selection and implementation of supporting tools and techniques is vital to effective execution of VRM. Studies indicate that integrated systems are easier to achieve and maintain when compatible processes are used for the process [Izuchukwu 1996]. Careful selection of supporting tools and techniques will ensure that an integrated VRM process can be achieved and maintained. Use of a well-defined VRM process with integrated tools and techniques will streamline the process by minimizing redundant work.

A substantial portion of communication and documentation (in the form of records) is accomplished through use of control and inspection plans. These plans should include all validated KCs requiring special attention during production activities. Accuracy and effectiveness of these plans are highly dependent on proper use and application of tolerancing and dimensioning practices. During these practices it is vital that datums and indexing schemes are consistently used and coordinated between design and manufacturing activities. In almost all cases, poor application of tolerancing and dimensioning can render VRM activities useless when is comes to control of KCs.

1.2.3 Current Practice of Variation Risk Management

At this time, there are a number of different processes established to perform VRM. These processes are being applied across a range of industries, products and production volumes. As mentioned in the introduction, Key Characteristics Methods, Critical Parameter Management, 6 Sigma Design, Hardware Variability Control, Advanced Quality Systems, Variation Control and Dimensional Management are methodologies currently in use. All of these processes focus on managing variation at some level, but most of them are not effective throughout the entire product development. The few processes that do span a large portion of the product development process tend to suffer from poor alignment between supporting tools and techniques.

Most processes appear to have evolved through an ongoing implementation of individual tools and techniques used to address specific problems in the development process. Inadequate communication of process control parameters from Design to Manufacturing is an example of this type of problem. As VRM processes became formalized, they emerged as a collection of individual tools and techniques loosely associated under a common process name. In most cases final forms of VRM processes do not sufficiently address all requirements for variation risk management because of discontinuities existing in the overall process. Attempts to expand these processes in order to meet all VRM requirements are often hampered by incompatibility between existing tools and techniques and limitations imposed by their existing, fragmented VRM process. As a result, it may be necessary for companies to reengineer the entire VRM process in a manner that considers the complete VRM process from the start of development.

It is important to understand that VRM processes must be integrated with the development process. VRM is not a substitute for a good design process and should not be used to compensate for poor design practices. A common mistake that has been observed is using KCs to compensate for designs that are not robust. In these situations, designers identified parameters that prevent robustness as KCs when the design could be changed to resolve the problem. Although VRM supports development of robust designs, it is most effective when combined with sound design practices. It must be understood that VRM is most effective when the development process is well established and encourages good design practices. When this is the situation, VRM works to manage sensitive parameters that cannot be designed out cost-effectively given the current product, process and technology limitations.

1.2.4 Utilization of VRM

Research of the MIT KC Group has revealed that a wide range of companies are using VRM, although they may be referred to with different names. In the aircraft manufacturing and supply industry, Boeing, McDonnell Douglas, Northrop, Hughes, AliiedSignal, SundStrand, Lockheed Martin, General Electric and ITT are all pursuing use of these methods. In most aircraft applications contractual requirements are primary reasons for suppliers to use VRM methods. For all cases that involve military procurement, government agencies strongly encourage their

suppliers to use some form of KC identification. Several companies specializing in commercial goods have also implemented these methods. In the automotive industry, Chrysler, Ford and GM all use some form of VRM process and KC classification. These companies also require their suppliers to be in compliance with similar practices. As for consumer goods, Xerox, Texas Instruments, Kodak, HP and others are applying similar techniques in order to achieve higher quality goods and drive down product cost.

1.3 Overview of the Supporting Research

The research supporting this thesis identifies several stages that will lead up to development of a VRM Guideline. This VRM Guideline will provide a model process and a recommended set of tools and techniques that can support this model. The purpose of the first stage is to identify a method that can assess existing VRM processes. The second stage defines activities and requirements[9] of the VRM process. The third assesses individual companies to identify supporting practices and potential problems that should be considered during development of the guideline. The fourth stage evaluates effectiveness of existing tools and techniques in supporting VRM activities and requirements. The final stage will combine the results from all of the previous stages to develop a VRM Guideline that represents a complete process. Each of these research stages are detailed in the following discussion.

The research process began with identifying a method to assess existing VRM processes. The Product Development Space (PDS) was developed by the author for this purpose (see Figure 4). The PDS is a three dimensional space consisting of organizational functions, product development phases and product levels. Each point in the space represents a potential scenario that may involve KC information. Multiple scenarios exist because KC information is commonly associated with various product levels, organizational functions and product development phases. For example, a scenario involving *Design Engineering* during the *Detail-level Design* phase considering *Components* of the product will be a point that always involves

[9] Activities and requirements will be considered the set of activities, functions, and criteria that "must" or "should" be satisfied by the functions/stages of the VRM process or by the process as a whole.

KC information. By identifying all points in the PDS that involves VRM information, it is possible to visualize interactions[10] representing VRM activities. For the purpose of this research, the PDS will help establish a basis to assess existing processes, tools and techniques based on identified interactions resulting from VRM activities. Assessment results will directly support development of the VRM guideline.

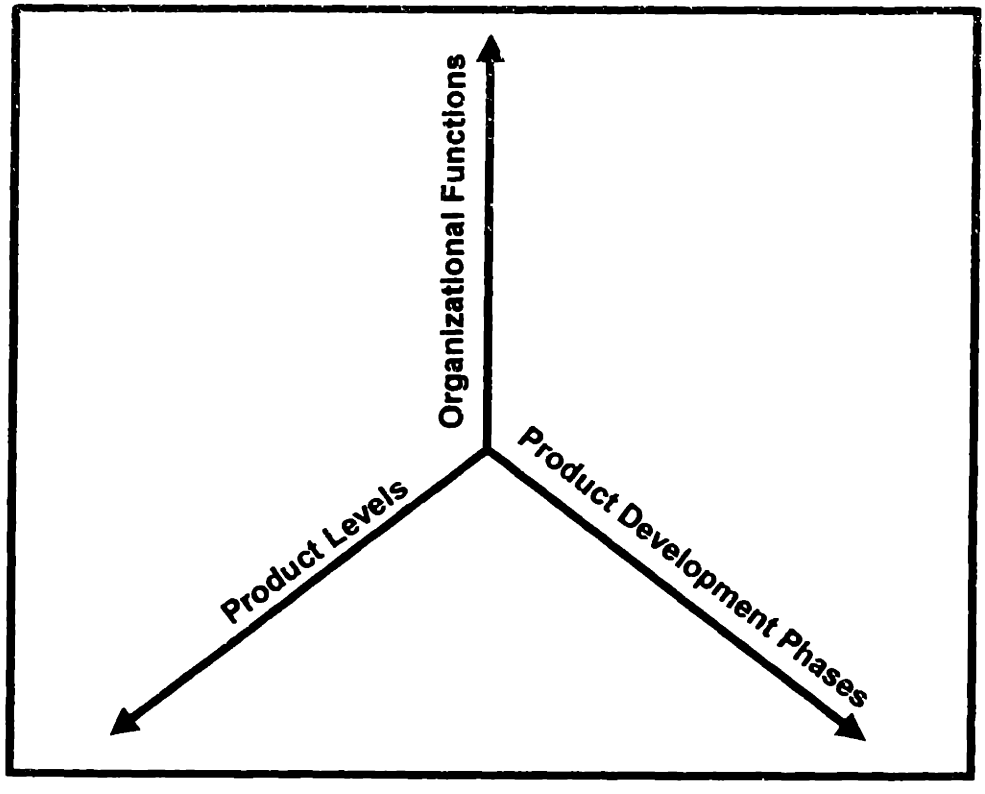


FIGURE 4: THE PRODUCT DEVELOPMENT SPACE

Establishing requirements for a complete VRM process is the second stage of the research. Requirements will be determined from three primary sources. The first set of requirements will be determined from the activities identified within the PDS as discussed in the previous paragraph. These will be considered the assessed needs for the process. The second source of requirements will be needs that were captured during the 1997 Key Characteristics Symposium. These represent stated customer requirements for the VRM process. The final source is

[10] Interactions refer to the exchange of VRM information between the organizational functions, the development process and the product levels as seen in the Product Development Space.

requirements imposed by the elements presented in the MIT Key Characteristics Maturity Model. These requirements are identified process needs. Each of these sources are considered independently and then combined. Additional needs and requirements are added based on the author's understanding of VRM. The final list will represent the identified complete VRM requirements.

The third stage of the research assesses individual companies to identify existing supporting practices and potential problems. VRM activities and requirements will define the assessment basis. One objective of the assessments is to reveal the potential problems in existing processes. A second objective is to identify supporting practices that will support a complete VRM process. These practices include selected tools and techniques, defined process objectives, coordinated process routines, established application schedules, assigned responsibilities and other details of this type. The results from these assessments will be used to support development of the VRM guideline.

Because of the importance of proper tool and technique selection, the forth stage will focus specifically on the use and implementation of these supporting items. The reviewed tools and techniques will be a collection identified during the company assessments. All of these items will be analyzed based their ability to support the VRM activities and requirements. The results from this analysis will lead to a recommended set of tools and techniques to support the guideline.

The final stage of the research develops a VRM Guideline based on results obtained from the previously discussed activities. The developed guideline will represent a complete process. It will include a defined process sequence, established procedures, and supporting practices. The results of this research should serve as a guide for additional company assessments and improvement activities.

1.3.1 Companies to be Included in the Assessment

Emphasis will be placed on the assessments of processes used by Boeing Commercial, Ford and Xerox. These companies were selected because of their diversified mix of products, range of product volumes, approach to product development and use of VRM processes.

2 Company Assessment Baseline

2.1 Chapter Introduction

This chapter outlines the company assessment baseline. The baseline is presented in two main parts. The first part defines VRM activities required to support interactions identified in the product development space. The second part will establish a set of requirements for a complete VRM process.

2.2 Defining VRM Activities base on Interactions in the PDS

The process of managing variation risk requires extensive interactions between organizational functions throughout the development phases at all product levels. The effectiveness of a VRM process depends on its ability to support these interactions in an efficient and organized manner. To determine the effectiveness of a VRM process, it must be possible to measure the level to which these interactions are supported through VRM activities. This requires the use of a method that can first identify the expected interactions, define VRM activities necessary to support these interactions and then determine how well these activities are supported.

For the purpose of identifying the necessary VRM activities, the author has selected the Product Development Space (see Figure 4). This space was selected because it represents the three areas where all VRM interactions can be observed. These areas, represented by the axis of the space, are organizational functions, product development phases and product levels. The space was also selected because it is a universal representation of all product development environments[11]. All VRM activities required to support the expected interactions can be identified in the product development space.

Functions, phases and levels for each axis are selected based on divisions observed over a wide range of companies. These observations were based on the assessed companies, as well as case

[11] The Product Development Environment will be defied as the entire set of resources, process, information and etc. required to support the development of a product.

studies and published material. The actual names selected for these divisions are based on what was found to be most common across companies; in some instances the selected names may differ slightly for a specific organization. Criterion for final selection was to ensure that all areas within a product development environment were represented and that they aligned with the companies being assessed. Table 2 presents the divisions that have been selected for each area.

2.2.1 Classifying the PDS Scenarios

As defined in Chapter 1, VRM interactions result from VRM activities involving organizational functions, product development phases and product levels. These interactions appear as links between scenarios represented by the product development space. A scenario is defined as a point in the space (i.e. an organizational function, a development phase, and/or a product level). To identify these interactions, an evaluation of each scenario determines if it involves VRM information. During this evaluation each scenario is classified based on one of four possible states:

1. Always involves VRM information
2. Has a high occurrence of involving VRM information
3. Has a low occurrence of involving VRM information
4. Should not require VRM information

Product Levels	Organizational Functions	Product Development Phases
1. Market Segment	1. Customer/Customer Representation	1. Concept and/or Strategy
2. Product Platform	2. Sales and Marketing	2. Technology Development and Refinement
3. Enabling Technology	3. Management/Corporate	3. Specifications and Configuration
4. Specific Product	4. Supporting Services and Resources	4. System Level Design
5. Systems or Assemblies	5. Information Systems	5. Detail Level Design
6. Subassemblies or Modules	6. Research and Development	6. Process Capability Assessment
7. Components	7. Cross-Functional Teams/Integrated Product Teams	7. Process and Tooling Design
8. Features	8. System Engineering	8. Process and Tooling Capability Refinement
9. Details	9. Design Engineering	9. Procurement of Sub-Assemblies and Components
10. Processes and Materials	10. Manufacturing Engineering and Tooling Design	10. Production and Manufacturing Ramp
	11. Quality Assurance	11. Full Scale Production and Manufacturing
	12. Industrial Engineering	12. Detail Level Inspection
	13. Factory and Tooling Fabrication	13. System Level Inspection
	14. Materiel	14. Product Distribution
	15. Suppliers	15. Product Service
	16. Product Service	16. Recycle
	17. Customer Service	

Table 2: Divisions Identified for the Product Development Space

Classifying these scenarios reveals the area within the product development space that is applicable[12] to the VRM process. Scenarios within the applicable space require continuous interactions supported by VRM activities. The author's evaluation of this applicable space reveals that interactions must always be supported for the scenarios that "always involved" or "has a high occurrence" of involving VRM information. This conclusion was based on the low

[12] Applicable refers to the group of scenarios within the PDS that involve VRM information and should be supported through interactions.

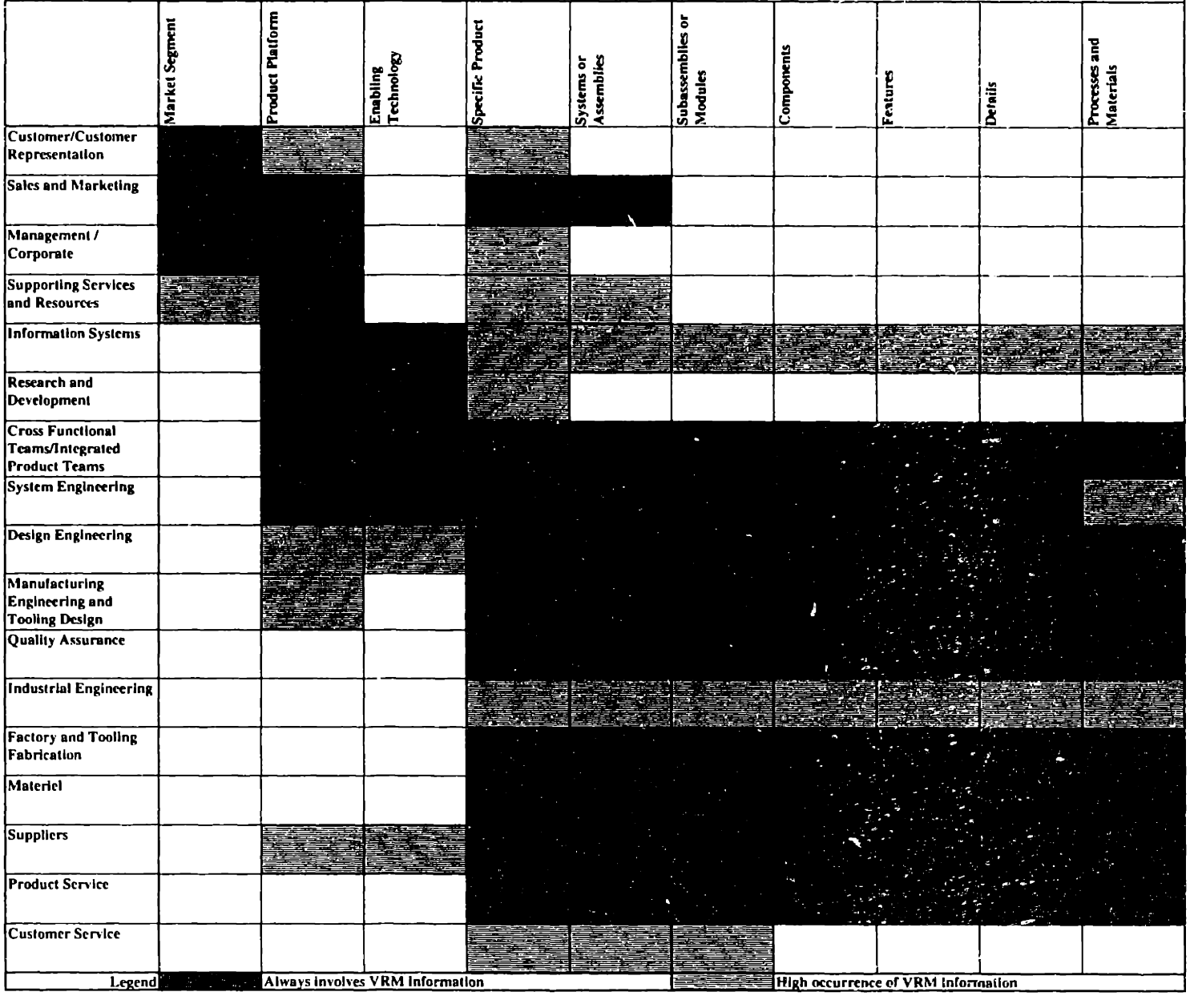
expected use of information existing at lower occurrence scenarios. In most cases, low occurrence scenarios contained information that is rarely used and generally will not appear as continuous VRM activities. Based on this understanding, only the two highest occurrence scenarios are considered for VRM interactions and activities.

For the initial PDS evaluation, the full three-dimensional (3D) area is used to evaluate VRM interactions. The full 3D area identifies over 2700 scenarios that could potentially involve VRM information. Results from the mapping reveal that there are approximately 700 scenarios that fall into the top two classifications ("always" and "high occurrence" of KC information). These 700 scenarios represent the VRM applicable space. Complexity of the three-dimensional information demands some level of simplification. To perform the simplification process, the 700 scenarios are evaluated for trends or generalizations that would accurately reflect this three-dimensional information. Conclusions from the simplification analysis reveal that results could be accurately represented using averages or combined scenarios when observed from three primary views. The primary views are defined as the Development Process-Product, Development Process-Organization and Product-Organization two-dimensional views. All of the information necessary to evaluate VRM interactions can be identified from these three primary views presented in Figures 5, 6 and 7.

Figure 5. The Development Process-Product View

Figure 6. The Development Process-Organization View
Concept and/or Strategy
Technology Development and Refinement
Specifications and Configuration
System Level Design
Detail Level Design
Process Capability Assessment
Process and Tooling Design
Process and Tooling Capability Refinement
Procurement of Sub-Assemblies and Components
Production and Manufacturing Ramp
Full Scale Production and Manufacturing
Detail Level Inspection
System Level Inspection
Product Distribution
Product Service
Recycle
Customer/Customer Representation
Sales and Marketing
Management / Corporate
Supporting Services and Resources
Information Systems
Research and Development
Cross Functional Teams/Integrated Product Teams
System Engineering
Design Engineering
Manufacturing Engineering and Tooling Design
Quality Assurance
Industrial Engineering
Factory and Tooling Fabrication
Materiel
Suppliers
Product Service
Customer Service
Legend
Always involves VRM information
High occurrence of VRM information

Figure 7. The Product-Organization View



2.2.2 Development Process-Product View

The first view considered is the Development Process-Product View (see Figure 5). This view displays KC scenarios for all product levels throughout phases of the development process. Identified scenarios in this view indicate that numerous product levels must be considered for potential VRM information. Evaluation of these scenarios indicates that interactions will be expected to occur up and down product levels at each phase of development. The identification, assessment, and mitigation activities must be capable of supporting these identified interactions. These identified interactions are listed below and figure 8 provides a general representation for each described interaction.

1. The **identification interactions (product-focused)** are a result of scanning[13] the product levels for potential KCs by comparing them to the product-process requirements. The KC flowup/down procedure ensures that product-process requirements, product-level impact(s), variation-source parameter(s) and relationships between them are identified. Collected information will be used to determine the probability and cost of KC variation.

2. The **assessment interactions (product-focused)** result from collecting information from different product levels required for qualitative or quantitative assessments. The KC flowup/down will help to identify the product level relationships and dependencies that must be considered during assessment.

3. The **mitigation interactions (product-focused)** will result from review of product levels information when determining the effectiveness and impact of mitigation alternatives. Product level reviews are required to determine the impact of selected mitigation alternatives on all product levels and to select the most effective level in the product to apply mitigation strategies. One or a combination of the following mitigation strategies must be selected: design changes, process changes, control/inspection and variation reduction.

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[13] Scanning is defined as the process iterating through the product levels looking for potential KCs.

A second group of interactions identified in the Development Process-Product view will occur between the product development phases. These interactions are represented by the information transfer illustrated at the bottom of Figure 8. As developments proceed, interactions are necessary to ensure the transfer of information between phases of ongoing identification, assessment and mitigation activities. This group of interactions is defined as follows:

4. The **documentation and communication interactions** will support the general transfer of VRM information between development phases and VRM stages. These interactions are primarily documentation and communication of VRM information for continued use over time. The documentation and communication will include both specific project information and multiple development (legacy and reuse) information.

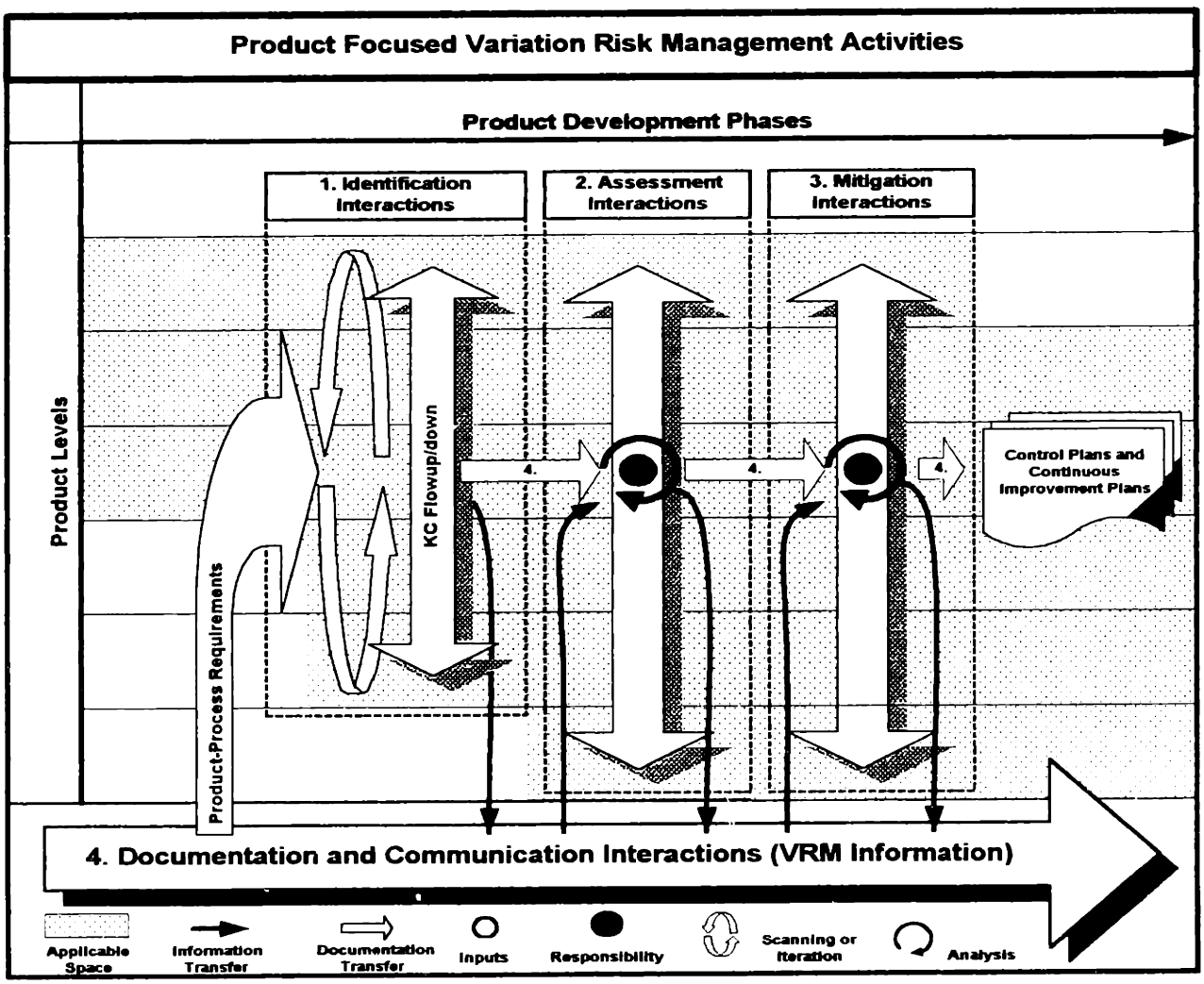

FIGURE 8: ILLUSTRATION OF PRODUCT FOCUSED INTERACTIONS

2.2.3 Development Process-Organization View

The second view to be considered is Development Process-Organization (see Figure 6). This view displays KC scenarios relevant to each organizational function throughout the product development process. This view reflects organizational-focused interactions necessary to support identification, assessment and mitigation activities and their relationship to the communication and documentation interactions. The organizational-focused interactions are identified in the following descriptions. Figure 9 provides a general representation of these organizational-focused interactions.

5. The **identification interactions (organization-focused)** will result from any interactions between organizational functions necessary to support the identification activities. These interactions will start with collection and review of the product-level requirements. Inputs must be obtained from organizational functions to support identification activities performed by CFTs. The organization-focused identification interactions must also help to coordinate activities between groups to ensure the overall product is adequately considered.

6. The **assessment interactions (organization-focused)** will result from interactions between groups during assessment activities. In most cases, assessment of a potential KCs will be led by a single organizational function, but the activities require input and/or information from multiple organizational functions for support.

7. The **mitigation interactions (organized-focused)** will result from interactions between groups necessary to support the mitigation activities. All mitigation alternatives should be selected based on a collaborative decision making process. These interactions are necessary when considering the impact of mitigation alternatives on all organizational functions.

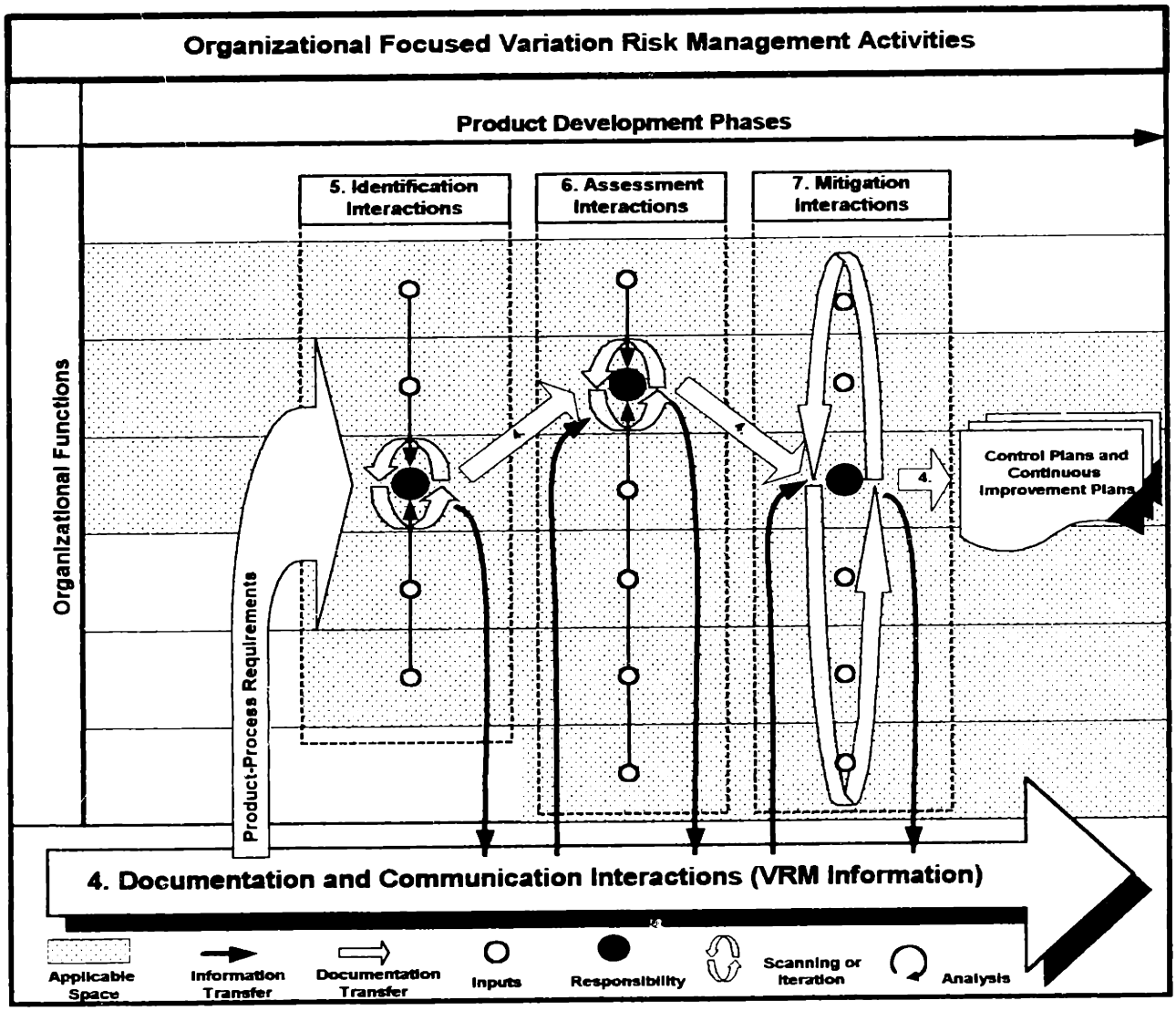

FIGURE 9: ILLUSTRATION OF ORGANIZATIONAL FOCUSED INTERACTIONS

2.2.4 Product-Organization View

The Product-Organization view remains to be considered (see Figure 7). This view displays the applicable scenarios relevant to each organizational functions and specific product levels. This view does not reflect any new interactions.

2.2.5 Summary of Identified VRM Activities

Evaluation of the primary views has resulted in identification of seven areas of interactions. Each of these interactions must be supported by specific VRM activities. The required activities are summarized in Table 3. This list of activities is used for the company assessments.

During the company assessment, the VRM process and the supporting tools and techniques will be evaluated based on their ability support these defined VRM activities. The measurement will be accomplished by performing a general review of the VRM process and supporting tools and techniques and categorizing them into these seven defined activities. Once categorized, a general review of supporting practices and potential problems will be discussed for each defined activity.

There are two main objectives when evaluating VRM activities. The first objective is to identify supporting practices and potential problems that exist when processes. The second objective is to identify individual tools and techniques that support the VRM activities. Company assessment surrounding these VRM activities will help identify the general process application, supporting practices and potential problems must be addressed during development of the guideline.

VRM Activities identified in the Product Development Space
1. **Identification activities (product-focused)** start with the identification of product-process requirements and flowing them down to part detail levels. The flowup and flowdown procedures ensure that the system KCs(s), sub-system KCs and feature-level KCs are systematically identified and their relationships explicitly captured.
2. **Assessment activities (product-focused)** use the KC flowdown along with cost and capability data to identify KCs at a high risk (either a high probability of occurring and/or high cost of failure).
3. **Mitigation activities (product-focused)** identify and select the best process for reducing the impact of variation. There are four alternatives that can be implemented separately or together: design changes, process changes, control/measurement, and process variation reduction.
4. **Documentation and Communication activities** support the capture and transfer of VRM information. In addition, these documents capture reuse/legacy information.
5. **Identification activities (organization-focused)** require organizational functions (including suppliers) and CFTs to perform and coordinate KC identification.
6. **Assessment activities (organization-focused)** require cross-organizational efforts. Of the three VRM stages, assessment requires the most amount of cross-organizational coordination. Assessment requires input from and coordination between multiple organizational functions to accurately consider the risk of KCs. Risk, as defined above, is a combination of the cost of a failure (set by the design organization) and the potential for that failure (set by the manufacturing process).
7. **Mitigation activities (organized-focused)** require collaboration between multiple organizations to select effective mitigation alternatives. All mitigation alternatives should be selected based on a collaborative decision that considers the overall product.

Table 3: Summary of Interaction Areas Identified in the PDS

2.3 Establishing the System-Level VRM Requirements

The second part of the VRM process assessment basis will include a set of system-level requirements. The system-level requirements will define what a VRM process "must" and "should" perform in order to be considered a complete VRM process. These requirements will apply to all VRM functions.

VRM activities and requirements are obtained from a range of sources. These sources reflect the assessed, stated and identified customer needs for the VRM process. The Product Development Space, Key Characteristics Symposium and MIT Key Characteristics Maturity Model are used as the primary source for VRM requirements. Each source is evaluated independently and the results are combined into a final set of VRM requirements. The following discussion details definition of the VRM requirements.

2.3.1 Requirements Identified from the Product Development Space

Interactions identified from the Product Development Spaces will impose a set of requirements on the VRM process. An analysis of these interactions reveals requirements that need to be placed on the VRM functions.

Activities and interaction statements 1 and 5 support a set of requirements that must be placed on the identification function. Based on the statements, identification interactions require a continuous process that can be applied by multiple functions for multiple product levels. These interactions must support identification of relationships between the product-level requirement(s), the product-level impact(s) and the variation-source parameters. The identification process must also be coordinated between the organizational functions. There must also be documentation and communication identification information to support ongoing VRM activities. These requirements can be summarized as follows:

1. Identification must review all product levels for potential KCs.
2. Identification activities must encourage all organizational functions to evaluate designs for potential KCs. This identification should be performed by both Cross-Functional Teams and individual organizational functions.

3. Identification must determine relationships between product-level requirements/impacts and sources of variation with use of a KC flowdown.
4. Identification must be coordinated between organizational functions.
5. Identification should be completed for each phase of the development starting with early development phases. This requirement ensures KCs are identified for assessment/mitigation before the product advances to later development phases.
6. Identification must exchange information in a format that supports documentation and communication functions. This format should clearly reflect traceability, classification, flowdown and other information that is required during assessment and mitigation.

Activities and interaction statements 2 and 6 support a set of requirements that must be placed on the assessment function. Based on the statements, assessment interactions must consider relationships between product levels. The assessment function must review KC flowdowns and refine them based on the assessment results. The assessment function must support inputs at product levels and organizational functions that are necessary to complete assessments. The function must provide information necessary to support documentation and communication. These requirements can be summarized as follows:

7. Assessment must review and refine identification information (potential KCs and KC flowup/down).
8. Assessment must consider information from individual levels and/or systems of the product that will/can be impacted by KCs.
9. Assessment must obtain inputs/information necessary for assessment from multiple organizational functions (internal and external) and/or through Cross Functional Teams.
10. Assessment must exchange information in a form that supports documentation and communication.

Activities and interaction statements 3 and 7 support a set of requirements that must be placed on the mitigation function. These statements indicate that mitigation activities must consider information from multiple product levels. Mitigation alternatives must be determined based on a collaborative decision between organizational functions. Identification and assessment information must be considered while selecting mitigation alternatives. And mitigation must provide information in a form that supports documentation and communication. These requirements can be summarized as follows:

11. Mitigation should consider multiple product levels during mitigation selection.
12. Mitigation must be a collaborative decision between multiple organizational functions (internal and external) and/or Cross Functional Teams.
13. Mitigation must consider information provided from identification and assessment activities.
14. Mitigation must obtain and provide information in a form that supports documentation and communication. This requirement ensures that all mitigation activities are justified and clearly understood for reuse or troubleshooting measures.

Activities and interaction statement 4 supports a set of requirements that must be placed on documentation and communication. This statement indicates that documentation and communication must support transfer of VRM information between development phases and VRM functions. The exchanged information must be in a form that can be used by multiple organizational functions. Information exchange must also support use/reuse of VRM information from other developments. These requirements can be summarized as follows:

15. Documentation and Communication must support exchange of information throughout and between developments. This requirement ensures KC information is available and accessible to all developments.
16. Documentation and Communication must support exchange of information between primary VRM stages/functions.
17. Documentation and Communication must capture information necessary for reuse/legacy data.

Evaluation of the Product Development Space and identified interactions has revealed several requirements that must be consider in the VRM requirements. A summary table of the identified requirements, organized according to the VRM functions, has been included in Appendix A.

2.3.2 Requirements Derived from the KC Symposium Material

Information collected from the 1997 KC Symposium proceedings will be considered a direct source of customer requirements for VRM processes. The Key Characteristic symposium was held at Massachusetts Institute of Technology on January 15th and 16th of 1997. This symposium was jointly hosted by Leaders for Manufacturing and Manufacturing Technology, Wright-Patterson Airforce Lab and MIT by Anna Thornton, an Assistant Professor in the Mechanical

Engineering Department. The symposium was used to bring experts from a variety of companies together to share experiences, successes, and problems with VRM processes. The symposium summary information is a collection of stated customer needs that were captured during open forum and focused group discussions. The resulting list of customer needs reflect current barriers and future goals for VRM as seen by industry representatives. Evaluation of these stated customer needs suggest requirements that should be imposed on VRM processes to ensure that current problems are addressed and the future goals are met.

The symposium summary information should be considered a universal set of customer needs. This universality is based on the involvement of eleven independent companies who use some level of VRM. These companies provided insight on design and production of products ranging from aircraft to cameras, for a wide range of customers. In addition to a variety of companies, there was also a diverse group of individuals from academia who participated in the symposium. Most of these individuals are extremely knowledgeable on alternative applications of VRM. Inputs from these individuals provided additional perspectives on VRM applications. The complete list of participants and summary information can be found at the following wed site: http://cardamom.mit.edu/KC/97conf.html.

Analysis of the symposium information was performed through a series of steps. The first step was to review the summary information and identify all statements that should impose some level of requirements on the VRM process. These statements are drawn from both current barriers and future needs. The second step involved organizing these statements according to the VRM functions they impact. The final step involved defining a group of requirements that satisfied the selected statements.

Results of the analysis have been presented in table form and can be found in Appendix B. The table is organized according to the VRM functions. For each function the identified symposium summary statements are listed in the left column. All defined requirements derived from these statements are listed in the right column. This list of derived requirements will be used to form the combined VRM requirements.

2.3.3 Requirements Based on Elements of the KC Maturity Model

Elements of the MIT Key Characteristics Maturity Model define the final set of VRM requirements. As mentioned in the introduction chapter, the KC Group identified these elements as vital enablers for effective execution of VRM. During company benchmarking, emphasis was placed on how well the VRM process performed in the product development environment. Because of this emphasis, any requirements identified from the elements are required to support a complete VRM process.

Analysis of the KC Maturity Model was performed by identifying potential impacts of each individual element on functions of the VRM process. The maturity model consists of 22 elements with four levels of maturity defined for each. The levels of maturity define the expected activities that should be performed to support each element. These levels are divided into "not used at all", "reactive", "semi-proactive", and "fully proactive". The complete maturity model has been included in Appendix C. During the analysis, each element was considered in context of the higher levels of maturity. The objectives of the analysis are to identify all requirements that were necessary to achieve the more proactive level of maturity.

Results of the analysis provided several requirements that must be imposed on VRM functions. The results are presented in table form and displayed in Appendix D. The table includes definitions, impacted VRM functions and defined requirements for each element in the maturity model. These requirements are considered in the combined set of VRM requirements.

2.3.4 Summary Identified VRM Requirements

A final set of requirements is established to represent the results of the preceding three sections. This combination of sources should provide a universal set of requirements that are independent of any particular product, product volume or customer group. Combination of these sources establishes a complete set of requirements for VRM processes. These requirements are used to assess VRM processes for overall effectiveness. Table 4 has been used to present the final combined list of VRM process requirements. The requirements have been organized according to VRM functions. This final list is used for the individual company assessments.

Variation Risk Management Requirements

Identification

1. KCs must be identified at each product level (i.e., system-level, sub-system level, and feature-level).
2. Identification must be shared and coordinated among organizational functions and CFTs.
3. The KC flowdown must capture both the individual KCs as well as relationships between them.
4. The identification process must result in a set of documents that contain the supporting information for assessment and mitigation.
5. Both functional and dimensional parameters must be evaluated for potential KCs during identification.
6. Identification must be linked to and motivated by customer requirements (internal or external).
7. Identification activities should occur throughout all development phases.
8. Identification should consider New Technology as a source for potential KCs.

Assessment

1. Assessments should consider individual feature variation and the impact of feature variation on system requirements using KC flowdowns.
2. Assessment activities must be shared and coordinated among organizational functions and CFTs.
3. Information/documentation from assessment activities must be maintained and accessible.
4. Assessment must be used to validate potential KCs before they are considered for mitigation.
5. Assessments of robustness should be based on quantitative measures through use of hardware, analytic models and/or computational systems.
6. Assessment should measure the impact of dimensional variation on functional performance.
7. Assessment should use process capability feedback information for the analysis whenever possible.
8. Assessment should prioritize validated KCs to ensure proper application of mitigation alternatives.

Mitigation
1. Mitigation activities must consider the impact of the mitigation alternatives on the overall product. 2. Mitigation must be a collaborative decision between multiple organizational functions (internal and external). 3. Mitigation activities and decisions should be documented. 4. Mitigation activities must be prioritized according to the risk of KCs. 5. Mitigation should select alternatives that support robust designs helping to minimize the total number of KCs needing to be controlled in production. 6. The selection of a mitigation strategy should be based on the cost and cost benefit data.
Communication and Documentation
1. Documentation and Communication must support the exchange of information throughout and between developments, between organizations and throughout VRM stages (identification, assessment, and mitigation). 2. Documentation and Communication must support flowdown and traceability of KC information. 3. Documentation and Communication must support process capability feedback for identification, assessment and mitigation functions. 4. Documentation and Communication must capture information necessary for reuse/legacy data. 5. Documentation and Communication must provide information necessary for measurement and inspection plans.
Documented Instructions
1. Documented instructions must have clearly defined goals and objectives for VRM. 2. Documented instructions must provide sufficient training and supporting process material. 3. Documented instructions must ensure a consistent set of definitions and/or classifications is established and used. 4. Documented instructions should communicate the activities required when a KC is identified. This ensures that all organizational functions are aware of the consequences and/or reactive measures that result from a KC classification.

Table 4: The VRM Process Requirements

3 Assessment of Boeing's VRM Process

3.1 Chapter Introduction

This chapter provides an overview and assessment of variation risk management activities for Boeing Commercial Aircraft Group. The chapter is presented in three parts: a general overview of KC definitions and classifications and VRM processes; an assessment of the current practices; and a summary.

3.2 General Process Overview

The goal of the following three sections is to identify the benefits and shortcomings of Boeing's VRM practices. The assessment reviews Boeing's documented material for the Hardware Variability Control (HVC) and Advanced Quality Systems (AQS). Because the application of HVC and AQS varies across divisions, the analysis is based on both documented materials and Boeing employee interviews.

The Boeing Commercial Aircraft Group division produces the 737, 747, 757, 767, and 777 aircraft. These products are considered complex designs produced in relatively low volumes. Most aircraft are designed or redesigned jointly between internal teams and external suppliers who have both design and production responsibility.

The interviews upon which this evaluation is based were performed through on-site visits and off-site discussions. The following manuals were referenced:

Advance Quality System D1-9000, July 1996
Advance Quality System: *Key Characteristics*, D6-55596 TN, Revision A, 1992
Advance Quality System: *Training*, D6-82019, November 1997
Advance Quality System Tools D1-9000-1, (Draft) September 1997
Hardware Variability Control: *Designing and Building for Advanced Quality*, Desktop Guide, D6-57000TN, Revision I, February 1996

Hardware Variability Control: *Establish Product Requirements*, 5G69, Revision B, July 1996

Variation Control: Linking Hardware Variability Control and Advanced Quality System D1-9011, November 1996

3.2.1 KC Classifications and Definitions

Boeing uses only one form of classification called Key Characteristic. The Hardware Variability Control (HVC) desktop manual defines Key Characteristics as:

> *Attributes or features (dimensions, specifications) of a material, part, assembly, installation, or system in which variation from nominal has the most adverse effect upon fit, performance or service life.*

In general, Key Characteristics are subject to Statistical Process Control (SPC) and measurement in the production environment.

Key Characteristics are designated on the drawings and through supporting documentation. They are designated with the key symbol and an alpha designator[14] (e.g., KEY and A, B, C). There is generally no distinction made between a potential KC and a validated KC[15].

During the design process KCs help coordinate datum and index schemes. Because datum and index transfers can introduce significant variation, designers are supposed to minimize the datum transfers where a KC is involved. In addition, all dimensional KCs must have a datum reference and there must be consistency between the datum and tool indexing up and down the Drawing and Build Trees. In some cases major tool-to-part indexing features are identified as KCs. The use of KCs to align the datum and index schemes has resulted in immediate and noticeable improvements for Boeing.

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[14] The alpha designators track the individual KC in conjunction with particular part numbers.

[15] A Validated KC is one that must be controlled using SPC or inspection because the design is not robust to existing variation. A Potential KC may or may not be at risk.

In most cases, KCs are related to top-level airplane and customer requirements. Other KCs are derived from produceability requirements. From the top-level requirements, KCs are supposed to be flown-down through the Drawing and Build Trees. These trees are primarily used to indicate the relationship between engineering drawings, illustrating the assembly sequence for the airplane. Additional supporting documentation is used to communicate KCs from top-level design activities to production and inspection phases. These documents include Airplane Interface Documents, System-Level Requirements, Lofting Requirements, Design Requirements and Objectives and Configuration Control Documents. The information in these documents can include drawings that outline major aircraft sections, engineering specifications that define product performance, and general statements that communicate product objectives.

3.2.2 Overview of the VRM Process

At the time of this assessment there were two VRM processes: one for internal use titled Hardware Variability Control and another for external use titled Advanced Quality Systems (AQS). For the purpose of this assessment, the HVC and AQS processes will be considered separately.

3.2.2.1 The Current Internal Process

Hardware Variability Control (HVC), the internal process for variation risk management, outlines a method for cross-functional management of variation during design and build processes. The HVC process is intended to provide a systematic approach to variation risk management. The primary objective for HVC is to control variation where it has the greatest impact on the overall product.

Boeing defines hardware variability as the deviation from the specified nominal value. HVC is based on the premise that controlling hardware variation will have a direct impact on the fit (how efficiently the plane can be built), performance (how well the airplane works and looks), and service life (how long the aircraft works and looks good). By improving these three areas

through the reduction of hardware variation, Boeing will help control cost and increase customer satisfaction.

The HVC documentation is based on Dr. Edward Deming's Plan-Do-Check-Act cycle. Emphasis is placed on the planning stage with each phase building on the activities performed in previous stages. The goal is to achieve "built-in" design and manufacturing quality. These four phases are briefly discussed in the following paragraphs.

3.2.2.1.1 The Plan Phase

The Plan Phase is used to initiate the HVC process and has four defined steps :1.) define the end user requirements for the product; 2.) establish the supporting CFT structure; 3.) perform the cross functional activities; and 4.) complete the documentation, tooling and training necessary to begin production ramp. Product requirements are generated by Sales and Marketing, Regulatory Agencies, Operations, Customer Service, Customer Representatives and Aircraft Design Members. The Concurrent Cross-Functional Teams (CFT) are then responsible for the flowdown of these requirements to the detailed part design. This flowdown supports identification of KCs throughout the product. The final step of the plan phase is developing a measurement process for the KCs identified by the CFTs. The Build Position Control Document, Functional Test Drawing Document and Process Control Documents are all used to outline the measurement and control activities to be performed during the check phase.

3.2.2.1.2 The Do Phase

The do phase contains one main step, which is to build and measure the product. This involves building the product, measuring key characteristics, and recording the measurement on statistical process control charts. These activities must be done in accordance with the documented standard process defined in the Plan Phase. The information obtained from the Do Phase will be used during the Check Phase to determine the effectiveness of the process.

3.2.2.1.3 The Check Phase

The Check Phase is used to determine if the product meets the product requirements by measuring the product both before and after delivery. Before delivery, these measurements determine if the process is in statistical control and capable of meeting the specifications. After

delivery, the activities check the final product quality. The results from the Check Phase are fed into the Act phase.

3.2.2.1.4 The Act Phase

The Act Phase has two steps. If the product and/or process are found to meet the customer requirements, the product/process will be considered for process acceptance. If the product does not meet the customer requirements, it must be considered for process improvements. All products and/or processes that go through the process improvement step must repeat the Plan-Do-Check-Act Phases; continuous improvement efforts involve repeating the Plan-Do-Check-Act phases.

3.2.2.1.5 Internal Process Summary

Interviews have revealed that the HVC process is well established but is used as a framework rather than as a detailed how-to-guide. Because of the differences between divisions and programs, the HVC process is often customized for specific initiatives. This has slowed the universal acceptance of the HVC process.

Interviews reveal two key problems with the current HVC implementation: too many KCs are identified and often identified too late. CFTs tend to identify KCs late in the design process and do not prioritize them. As a result a large numbers of KCs are identified and must be controlled in production. In addition, although HVC documents imply a proactive approach, interviews have indicated that HVC is often implemented reactively. In many situations, identification, assessment and mitigation activities are initiated after the product goes into production and problems begin to surface.

3.2.2.2 **The Current External Process**

The Advanced Quality System (AQS) contains the quality requirements for Boeing suppliers and focuses on product and process improvement. It is used by external suppliers, but can be used by internal suppliers as well. It includes a strong emphasis on the VRM process. It is based on improving quality by systematically managing and reducing variation accomplished through process understanding, monitoring, and continual improvement. It is accomplished by applying

statistical, engineering and quality improvement tools. The AQS process begins with identification of Key Characteristics followed by statistical control and capability analysis of the identified KCs. A collection of tools supporting KC management has been outlined in D1-9000-1, the AQS tools manual.

The primary activities of the AQS process can be outlined in four steps. The first step is to perform a product, process and problem analysis. Step two identifies the Key Characteristics. Step three begins the quantification of variation associated with the KC; this is usually accomplished through control charts or other appropriate graphical methods. Once a KC is identified and the variation has been quantified, step four determines if the KC is in statistical control and the process is capable. If the KC is not statistical control, measures must be taken to make the process capable and/or bring it into control. The continuous application of these four steps is used to ensure all product/process are capable and in control.

The AQS requirements state that the supplier must evaluate a product for Key Characteristics if Boeing has not identified any. Additional KCs impacting the produceability of the sub-system may also be identified. All identified KCs must be documented on an AQS Control Plan or its equivalent. Unless otherwise stated, it is the supplier's responsibility to flow down KCs to subcontractors and ensure they too are in compliance with AQS requirements. When Boeing provides KCs, they are noted directly on appropriate documentation: Engineering/Build Drawing, Specification Control Drawing (SCD), Engineering Standard, Process Control Document (PCD), Purchase Contract, or CAD/CAM digital definition. Boeing identified and supplier identified KCs are controlled based on the AQS requirements.

The AQS process requirements state that a Boeing Company supplier must have the ability to determine and measure the variation of Key Characteristics confirming statistical control and capability. In addition, corrective action must be taken when a KC is not in control and/or not capable. All activities related to control of KCs must be documented and maintained for proof of compliance. Process capability and control data must be maintained for all KCs under process control; suppliers must maintain the proper procedures and records to prove AQS compliance at all times.

3.2.2.2.1 External Process Summary

Interviews reveal that while the requirements established by AQS are applied, external suppliers have flexibility on the overall process implementation. The AQS process was created to standardize the requirements placed on suppliers. As long as the supplier can prove they are in compliance with KC identification, control, and capability, the process they use to plan, execute, maintain and record the management of KCs is their choice.

The interviews have also indicated that although the AQS process helps to ensure supplier compliance to the VRM process, Boeing's processes are not always successful at ensuring coordination between internal CFTs and external suppliers. In many situations, KCs are identified by external suppliers and not by Boeing. When KCs are identified by Boeing, the AQS/VRM process is invoked. It is coordinated from the Boeing program through the Materiel Division to the supplier. Field representatives and AQS personnel in the Materiel Division support the supplier in their implementation of AQS on the identified KCs. Supplier data, such as statistical control charts, gage studies, DOEs and process capability data are available to Boeing.

When suppliers identify KCs, there is sometimes a limited exchange of information, especially in the form of feedback from Boeing; as a result proper VRM execution from top to bottom is not always accomplished.

3.3 Details of the Assessment

Chapter 2 outlined the basis for the individual company assessments. In this section the Boeing's process is compared to the assessment baseline. For each of the VRM activities and requirements, a brief statement indicates if and/or how the requirement is met. In addition, a subject rating (good, moderate or poor) is given for the VRM requirements in the second portion of the assessment.

3.3.1 VRM Activities

1. **Identification activities (product-focused)** start with the identification of product-process requirements and flowing them down to detailed part levels. The flowup and flowdown procedure ensure that the system KCs(s), sub-system KCs and feature level KCs are systematically identified and their relationships explicitly captured.

Supporting Practices:

- Drawing Trees, Schematic Trees, and Build Trees indirectly support the KC flowup/down.
- Identification is linked to and initiated by the identified top-level customer and product requirements. Airplane Interface Documents, System-Level Requirements, Lofting Requirements, Design Requirements and Objectives/Configuration Control Documents contain these top-level requirements.

Potential Problems:

- The Build and Drawing Trees do not explicitly capture the KC relationships between system, sub-system and feature KCs. This makes it difficult to trace the impact of variation through the assembly stages.
- Interviews have revealed that a clear systematic approach to the KC flowdown process has not been established. As a result, a variety of approaches are applied to a single product with limited consistency.
- Interviews indicate that classifications and/or definitions for KCs are not constant throughout the organization. This has led to misuse and misinterpretation of KCs. A common mistake is the use of KCs to reflect "design importance" for parameters that are not high cost or high risk.
- HVC tends to define KC identification as being performed during one phase in the product development; however, best practice studies indicate that KCs should be continuously identified throughout the product development.

2. **Assessment activities (product-focused)** use the KC flowdown along with cost and capability data to identify KCs at high risk (either a high probability of occurring and/or high cost of failure).

Supporting Practices:

- Process capability and measurement/gage system studies are required procedures of HVC. These studies quantify the variation introduced by the process and measurement systems.
- Statistical tools and analytical techniques are assessment activities that determine the impact of variation. These tools include Tolerance Analysis, Statistical Tolerancing, Sensitivity Analysis, Cause and Effect Analysis, Design of Experiments, Variation Investigations, ANOVA, CM4D, VSA and others. These tools, however, have not been systematically applied on all developments.

Potential Problems:

- The relationships between dimensional and functional variation sensitive parameters appear to be under emphasized. Assessments tend to be focused on either dimensional parameters or functional parameters, but the interactions between the two are not clearly understood.
- Because the KC Flowdown is not clearly defined in the identification stage, variation effects and/or sources are not easily traced.
- Interviews have revealed that blanket or historical (i.e., how it was done on the last program) tolerances are often used. As a result, tolerances at a sub-system or feature level often do not reflect design intent and/or performance requirements for the system. The lack of proper tolerance allocation makes it difficult to obtain accurate results from the assessment activities.

3. **Mitigation activities (product-focused)** identify and select the best process for reducing the impact of variation. There are four alternatives that can be implemented separately or together: design changes, process changes, control/measurement, and process variation reduction.

Supporting Practices:

- HVC and AQS outlines several mitigation alternatives that involve process improvements, redesign or tooling changes. One or a combination of these alternatives must be selected if the manufacturing specifications do not match the product specifications.
- Coordinated datums and indexes are used to reduce the impact of variation caused by misalignment between design, manufacturing and assembly.
- The Redesign Process, as defined in HVC, requires that a CFT first determine the source of variation and then select a mitigation alternative to resolve the addressed problem.

Potential Problems:

- Although HVC encourages the use of robust design as a method to reduce variation, Boeing depends heavily on SPC, measurement, and inspection for mitigation alternatives.
- The ability to choose effective quality plans is limited without a clear KC Flowdown. This leads to a large number of measurement points, which strains the limited measurement and control resources.

4. **Documentation and Communication activities** support the capture and transfer of VRM information. In addition, these documents capture reuse/legacy information.

Supporting Practices:

- Top-level requirements are defined and documented in the Airplane Interface Documents, System-Level Requirements, Lofting Requirements, Design Requirements and Objectives/Configuration Control Documents.

- The use of Engineering Drawings, Preliminary Schematics, Assembly Drawings, Build Position Control Drawings, Schematic/Drawing/Build Trees, Specification Control Drawings, and Material/Part/Process Standards are all used to document and communicate KCs.
- Functional Test Drawing Documentation and Datasets ensure proper measurement and control of functional system KCs.
- The Build Position Standard Process Book is used to coordinate tooling, manufacturing, process control, product measurement, system installation, and testing and communication required to monitor and control KCs.
- AQS requires extensive documentation of VRM information as a standard process for external suppliers. This information is used to ensure suppliers are in compliance with AQS requirements. Included in this documentation is the AQS Control Plan and SPC Datasets/Charts.

Potential Problems:

- The use of Drawing Trees, Schematic Trees, and Build Trees do not provide adequate KC flowup/down.

5. **Identification activities (organization-focused)** require organizational functions (including suppliers) and CFTs to perform and coordinate KC identification.

Supporting Practices:

- Build Position Owners (BPO) are responsible for coordinating activities with other BPO and CFTs regarding the identification of potential KCs.
- CFTs and the CFT structures are used to perform and coordinate KC identification.
- AQS is used to ensure external suppliers identify KCs. Suppliers are required to maintain records that show traceability and capability for all identified KCs.

Potential Problems:

- HVC should reflect that all organizational functions must participate in KC identification; this will be performed in addition to Cross-Functional Team involvement.
- Interviews have indicated flowdown of KC information to suppliers is not consistent. Furthermore, suppliers tend to manage KCs independent of internal organizations. This causes feedback to be poorly maintained or untimely. This discontinuity limits traceability of KC information between internal and external functions.

6. **Assessment activities (organization-focused)** require cross-organizational efforts. Of the three VRM stages, assessment requires the most amount of cross-organizational coordination. Assessment requires input from and coordination between multiple organizational functions to accurately consider the risk of KCs. Risk, as defined above, is a

combination of the cost of a failure (set by the design organization) and the potential for that failure (set by the manufacturing process).

Supporting Practices:

- Cross-Functional Teams are generally involved in or required to coordinate assessment activities. These activities include tolerance and capability analysis.
- Build Position Owners are established and required to confirm that all KCs impacting their build positions are properly identified and assessed. This assessment requires coordination with other BPOs and CFTs.
- Supplier interactions, in the form of Preliminary and Critical Design Reviews, help ensure suppliers have correctly performed KC assessments.
- Operator studies determine if process operators are potential sources of variation. These assessments often require interactions between several organizational functions.

Potential Problems:

- Although tolerance and process capability studies are performed before production begins, most assessments are done after production is started.
- Interviews have revealed that information needed for assessment activities is divided among organizational functions and is often difficult to find or obtain. Part of this problem is attributed to the lack of ongoing coordination between organizational functions and CFTs.

7. **Mitigation activities (organized-focused)** require collaboration between multiple organizations to select effective mitigation alternatives. All mitigation alternatives should be selected based on a collaborative decision that considers the overall product.

Supporting Practices:

- Cross-Functional Teams and Team Structures are intended to support interactions between organizational functions necessary for mitigation.
- Build Positions Owners are assigned responsibility to ensure KCs are properly controlled for their build position and coordinated with other build positions.
- Production is responsible for continual measurement and monitoring of KCs.

Potential Problems:

- Interviews have indicated that mitigation responsibility is often passed to downstream organizational functions. For example, rather than assessing and redesigning a system during the design phase, KCs and their tolerances are specified and handed to manufacturing for assessment and mitigation (control).
- Interviews indicate that a similar problem of late mitigation (as mentioned above) also occurs with suppliers.

3.3.2 VRM Requirements

Identification

1. **KCs must be identified at each product level (i.e., system-level, sub-system level, and feature-level).** *(Moderate)*

   BPOs and CFTs have responsibility for identifying KCs at each assembly stage or build position. However, systematic flowdowns are not always completed. Build Trees are used to record KCs identified for each build position.

2. **Identification must be shared and coordinated among organizational functions and CFTs.** *(Moderate)*

   CFTs and BPO are responsible for identification. However, in many situations identification is passed onto production and used during troubleshooting process production.

3. **The KC flowdown must capture both the individual KCs as well as relationships between them.** *(Moderate)*

   Build Trees are used to capture and communicate KCs, however, there is no means to identify relationships specific to KCs.

4. **The identification process must result in a set of documents that contain supporting information for assessment and mitigation.** *(Moderate)*

   The Key Symbol and alpha indicator identify all controlled KCs. However, there is little information recorded regarding classification, cost, relationships, criticality, importance, origination, responsible group, status (Potential vs. Validated), etc.

5. **Both functional and dimensional parameters must be evaluated for potential KCs during identification.** *(Moderate)*

   HVC focuses on dimensional KCs. There is no explicit method to handle the case where a dimensional KC drives a functional KC. For example, how wing alignment requirements affect flight characteristics (i.e., required trim).

6. **Identification must be linked to and motivated by customer requirements (internal or external).** *(Good)*

   Top-level requirements are identified and used to guide KC identification. This information is collected from Sales and Marketing, Operations, Customer Service, Regulatory Agencies, and Customer Representatives. Supporting materials include Design/System Requirements and Objectives, Configuration Control Documents, Airplane Interface Plans, Lofting Requirements and Preliminary Schematics.

7. **Identification activities should occur throughout all development phases.** *(Moderate)*

   Identification tends to be performed at one phase of the product development. Continued identification is performed in production, thereby supporting continuous improvement efforts.

8. **Identification should consider New Technology as a source for potential KCs.** *(Good)*

   Reviewed documentation briefly mentions New Technology as a source for potential KCs, however, most aircraft are comprised of technology that is well understood.

Assessment

1. **Assessments should consider individual feature variation and the impact of feature variation on system requirements using KC flowdowns.** *(Moderate)*

   Build and Drawing Trees support the KC Flowdown, but do not clearly reveal KC relationships; this limits the ability to assess impacts on the entire system. Assessments tend to be very feature oriented.

2. **Assessment activities must be shared and coordinated among organizational functions and CFTs.** *(Good)*

   CFTs, the CFT Structures and Build Position Owners help to facilitate this requirement. Interviews have indicated that suppliers are not always involved in assessment activities.

3. **Information/documentation from assessment activities must be maintained and accessible.** *(Moderate)*

   Few measures exist to capture and exchange assessment information. Capability-Tolerance Analysis, Risk Analysis Worksheets and FMEAs are occasionally used to capture assessment information.

4. **Assessment must be used to validate potential KCs before they are considered for mitigation.** *(Moderate)*

   Because there is no distinction between a potential KC and a validated KC, it is difficult to ensure all KCs are validated before being considered for mitigation. Interviews indicate that some KCs go without sufficient assessment before being placed on control plans.

5. **Assessments of robustness should be based on quantitative measures through use of hardware, analytic models and/or computational systems.** *(Moderate)*

   Analytical tools and computational models are not consistently used. Supporting tools include Tolerance Analysis, Statistical Tolerancing, Sensitivity Analysis, Design of Experiments, Variation Investigations, VSA and others. Interviews have revealed that only a limited number of identified KCs are assessed with these tools/techniques.

6. **Assessments should measure the impact of dimensional variation on functional performance.** *(Moderate)*

   Although both functional and dimensional KCs are considered, they tend to be assessed independent of one another. In many cases, relationships/interactions between functional and dimensional KCs are not clearly understood.

7. **Assessment should use process capability feedback information for analysis whenever possible.** *(Moderate)*

Process capability information is used during some assessments. The extent of its use is limited due to availability or accessibility of process capability data. Historical process information is required to be maintained through the HVC and AQS application, but locating, retrieving and interpreting this information tends to be difficult.

8. **Assessment should prioritize validated KCs to ensure proper application of mitigation alternatives.** *(Moderate)*

   Prioritization of KCs is not consistently performed. External suppliers occasionally use failure Modes and Effect Analysis (FMEA) to provide a qualitative prioritization of identified KCs. The occasional use of Risk Analysis Worksheet by internal teams also provides a qualitative prioritization. Interviews have indicated, however, that prioritization activities are generally limited.

Mitigation

1. **Mitigation activities must consideration the impact of the mitigation alternatives on the overall product.** *(Moderate)*

   The communication between CFTs is the primary method for determining the impact of a change on the overall product. In some cases, computational tools such as VSA quantify the impact of a change.

2. **Mitigation must be a collaborative decision between multiple organizational functions (internal and external).** *(Moderate)*

   The use of Cross-Functional Teams at the airplane-level and individual build positions is the primary means for supporting collaborative decisions during the mitigation phase. Interviews indicate that coordination with external suppliers is not always sufficient to support a completely collaborative decision process. Use of supplier design reviews encourages collaborative changes with external suppliers. However, internal and external mitigation activities tend to be managed independent of one another.

3. **Mitigation activities and decisions should be documented.** *(Good)*

   HVC and AQS require formal documentation and communication of final measurement schemes. This is primarily achieved through preparation of the Build Position Standard Process Books, Process Control Documents and AQS Control Plans.

4. **Mitigation activities must be prioritized according to the risk of KCs.** *(Moderate)*

   Interviews indicate identified KCs are often transferred to measurement or control plans without adequate assessment, mitigation or consideration of KC prioritization. Limited KC prioritization is performed.

5. **Mitigation should select alternatives that support robust designs helping minimize the total number of KCs needing to be controlled in production.** *(Moderate)*

Mitigation activities tend to be executed late in the development process, which limits the extent to which designs can be changed to achieve robustness. Several identified KCs are transferred to Control Plans without adequate consideration of mitigation alternatives.

6. **Selection of a mitigation strategy should be based on the cost and cost benefit data.** *(Good)*

   In situations where cost data is available, it is used for mitigation activities. In many cases cost data does not exist or it is extremely difficult and expensive to obtain.

Communication and Documentation

1. **Documentation and Communication must support exchange of information throughout and between developments, between organizations and throughout VRM stages (identification, assessment, and mitigation).** *(Moderate)*

   Documentation and Communication activities do provide support for exchange of KC information within and between developments, but it is generally in the form of product design documentation. There are limited tools to support information exchange specific to KCs (i.e., cost, Cpk, prioritization, risk, etc.)

2. **Documentation and Communication must support flowdown and traceability of KC information.** *(Moderate)*

   Build and Drawing Trees indirectly support the KC flowdown, but do not explicitly reveal KC relationships. No explicit means exist to support the flowdown and traceability of KC information.

3. **Documentation and Communication must support process capability feedback for identification, assessment and mitigation functions.** *(Moderate)*

   Process capability data is limited in its availability and accessibility. According to HVC and AQS process documentation, Statistical Process Capability Charts are required for all identified KCs. Feedback of process capability varies across developments.

4. **Documentation and Communication must capture information necessary for reuse/legacy data.** *(Moderate)*

   Based on interviews, a majority of developments are derivative designs. Several factors inhibit reuse of KC information and flowdowns; first, older designs were done without KC flowdowns; second, the original design intent is not known; third, KC flowdown methodologies are not consistent and the information is not always trusted. Measures are being put in place to support reuse/legacy data.

5. **Documentation and Communication must provide information necessary for measurement and inspection plans.** *(Good)*

   The Build Position Standard Process Book coordinates tooling, manufacturing, process control, product measurement, system installation and testing, and communication activities. AQS also requires a Process Control Plan to be maintained for all KCs.

Documented Instructions

1. **Documented instructions must have clearly defined goals and objectives for VRM.** *(Good)*

   Both HVC and AQS clearly reflect goals and objectives for variation risk management processes.

2. **Documented instructions must provide sufficient training and supporting process material.** *(Good)*

   Both HVC and AQS clearly emphasize training and outline when these activities should be performed. Training is generally provided based on group needs for each specific application. Coaches and Process Leaders are often established to ensure proper application of VRM processes. HVC Training Plans, HVC Process Instructions, AQS Process Instructions, and HVC/AQS training manuals make up this supporting documentation.

3. **Documented instructions must ensure a consistent set of definitions and/or classifications is established and used.** *(Moderate)*

   Definitions and/or Classifications exist, but are not well established. Interviews have identified this area as in need of improvement and additional clarification.

4. **Documented instructions should communicate activities required when a KC is identified. This ensures that all organizational functions are aware of the consequences and/or reactive measures that result from a KC classification.** *(Moderate)*

   Both HVC and AQS processes have instructions that outline expected reactions and/or implications associated with KCs. However, distinctions between a potential KC (a KC that may be a problem) and a validated KC (a KC that will definitely create a problem) is not made. Interviews indicate that interpretations of KCs vary which has led to misuse and overuse of KCs.

3.4 Assessment Summary

Assessment of Boeing's VRM process has revealed a number of supporting and unsupported activities and requirements. The following discussion summarizes these findings.

3.4.1 Supporting Activities and Requirements

Application of HVC and AQS is generally owned by cross-functional teams. Cross Functional Teams and Build Position Owners are assigned to major assembly positions, systems and subsystems. The hierarchical CFT structure supports the flowup and flowdown of KCs. The structure is also used to support collaborative assessment and mitigation decisions. Once in

production, the CFT structure is used to ensure that KCs are controlled. In addition, CFTs have the responsibility to resolve problems that still remain once production has begun.

HVC and AQS documentation includes goals, objectives and requirements for VRM. They are used extensively to support training for all organizational functions. The documentation is presented in a series of manuals that outline general practices and specific requirements for VRM processes. The training, provided to the team members and suppliers involved in new developments, is considered an integral part of VRM process for every development.

3.4.2 Unsupported Requirements and Activities

In general, VRM at Boeing is based on a single iteration during the main development cycle, which is then followed up by continuous improvement cycles during production. Although HVC encourages the process to be proactive, the actual execution tends to be reactive. This main iteration cycle tends to under emphasize assessment activities required to quantify the cost and potential failure of KCs. The single iteration tends to generate a large number of KCs resulting in significant measurement burden during manufacturing. Most of the KCs identified during design are sent directly to process control without proper consideration of other mitigation alternatives, such as design or process changes.

Almost all KC information is managed through product design documentation (i.e., drawings and quality control documents). The greatest problem with this scheme is the lack of a clear KC flowdown. As stated in previous chapters, the KC flowdown is critical to proper identification, assessment and mitigation activities. Without a clear KC flowdown it is difficult to identify sources of variation, contribution from individual variation sources and/or overall impact to the product. In addition, KC flowdowns encourage development of rational measurement plans.

4 Assessment of the Ford's VRM Process

4.1 Chapter Introduction

This chapter provides an overview and assessment of the variation risk management activities for the Ford Motor Company. The chapter is presented in three parts: a general overview of KC definitions and classifications and VRM processes; an assessment of the current practices; and a summary.

4.2 General Process Overview

The goal of the following three sections is to identify the benefits and shortcomings of Ford's practices for variation risk management. Because the application of VRM varies across the divisions, the analysis is based on a combination of documented materials and interviews of Ford employees.

The Ford Motor Company produces automotive vehicles, which are medium to high in design complexity and high in production volumes. Their products have a significant number of components, subsystems and systems obtained from suppliers. Many of these external suppliers are full service, providing both design and production services.

The interviews, upon which this evaluation is based, were performed through on-site visits and off-site discussions. The following manuals were referenced:

Advanced Product Quality Planning and Control Plan (APQP), Reference Manual, June 1994

Characteristic Classification, Procedure Number: PTP 07-101, 7/21/97

Dynamic Control Planning, Procedure Number: PTP 07-102, 7/21/97

Ford's Approach to Special Characteristics: Controlling FMEA Driven Characteristics1997 Key Characteristics Symposium Presentation by Cynthia A. Taaffee, 1/15/97

Global Dimensional Control Department: Dimensional Variation Analysis Definition Module, Vehicle Operations, Dimensional Control Department, Document 01-005, February 24,1997

Global Dimensional Control Department: Locator Definition Module, Vehicle Operations, Dimensional Control Department, Document 01-003, January 28,1997

Global Dimensional Control Department: Measurement Point Definition Module, Vehicle Operations, Dimensional Control Department, Document 01-002, January 28,1997

Measurement System Analysis (MSA), February 1995

Potential Failure Mode and Effect Analysis (FMEA), February 1995

Product Part Approval Process (PPAP), February 1995

Quality System Requirements (QS-9000), February 1995

Statistical Process Control (SPC), March 1995

The Strategy of Dynamic Control Planning, Training Reference Manual for Procedure PTP07-102

Total Vehicle Dimensional Control Discipline: Sheet Metal Presentation, Vehicle Operations, Dimensional Control Department, November 1995

4.2.1 Definition and Classifications of KCs

Ford uses a range of KC definitions and classifications. The primary designations fall into a group called Special Characteristics, which is the combination of undesignated or designated Critical and/or Significant Characteristics. The hierarchy for Special Characteristics is represented in Figure 10.

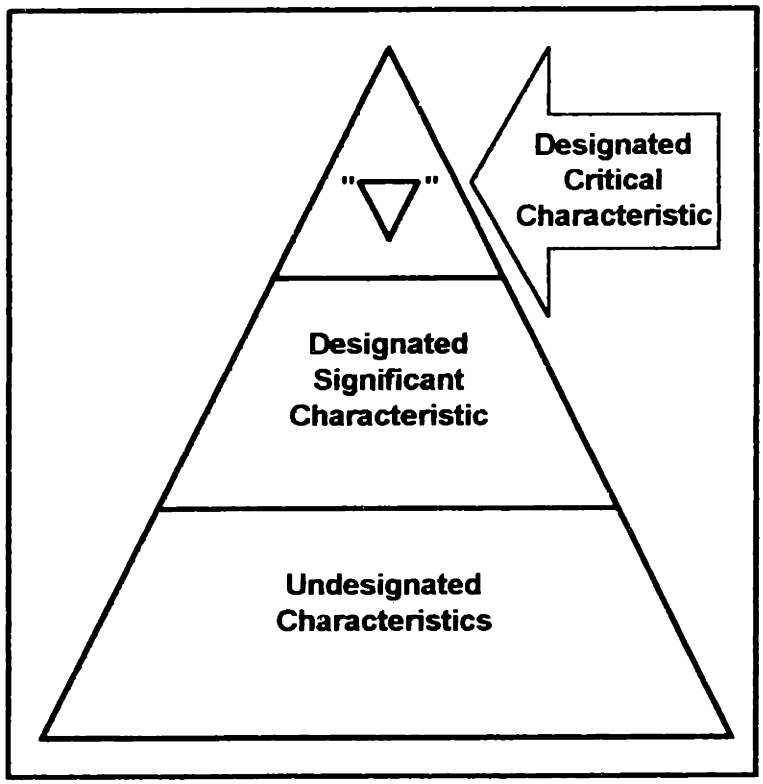

FIGURE 10: HIERARCHY OF SPECIAL CHARACTERISTICS

The Critical Characteristics (CC) are represented with an inverted delta (∇) and carry the greatest importance in terms of control and/or monitoring. Critical Characteristics focus on safety and regulatory requirements. Critical Characteristics are defined as follows:

> *Are those product requirements that affect compliance with government regulations or safe Vehicle/Product Function that require special actions or controls. Product or Process controls can include dimensional specification, test process, assembly sequence, tooling, joints, torque, welds, attachments, component usage, etc. Special Action/Control can include Manufacturing, Assembly, Suppliers, Shipping, Monitoring/Inspection actions-controls.*

Significant Characteristics (SC) use "SC" as a designation and are second in terms of importance. The Significant Characteristics should not be used to address safety and regulatory parameters. These characteristics are defined as follows:

Product and/or test requirements which are important for cost, safety and for where quality planning actions (i.e., special controls) must be summarized on a control plan.

Critical and Significant Characteristics are detailed on the control plans. Designated Special Characteristics require team sign-off by Product Engineering and Process Engineering Members, Manufacturing and Quality Members, Union Team Members of equivalent Product Personnel, Customers and others, as appropriate. Final agreement must be achieved between Product Engineering and Manufacturing Engineering. All Critical and Significant Characteristics require statistical control techniques to ensure they are capable and in control.

In addition to Significant and Critical Characteristics, Powertrain division also recognizes High Impact Characteristics (HIC). Powertrain defines High Impact Characteristics as:

Are potential critical and potential significant characteristics from Design FMEA (YC or YS) that do not require special control when evaluated on the Process FMEA.
Product or Process characteristics, when outside specified tolerances, which severely effect a particular process itself or subsequent operation.

High Impact Characteristics are "important" to the product or process. Powertrain uses HIC to added attention or control to characteristics that do not warrant special controls. High Impact Characteristics must be indicated on the control plan, however, statistical control is not a requirement.

The Dimensional Control Department, under Vehicle Operations, also has a set of KC definitions or classifications. This division manages the dimensional related characteristics primarily for the body structure buildups, interior trim subassemblies and installation, exterior ornamentation subassemblies and installation, and chassis subassemblies and installation. The group identifies Significant Features that are monitored and controlled in production. Significant Features are defined as follows:

Significant Features are areas of the component that have been defined as significant by the engineer. The decision is based on how the area of the part affects overall build, quality, or downstream users. When selecting measuring points, the team must ensure that certain points are used for the specific purpose of ensuring these significant features are met.

As indicated by the definition, measurement points must correspond to Significant Features; these are considered dimensionally important for appearance, fit and function concerns. All defined measurement points should be related to Significant Features.

Dimensional Management classifies the measurement points into five levels. Level one measurement points are used for tool buyoff and represent the maximum number of points to be measured from all systems. Level two points are a subset of level one used to monitor the Significant Features and ensure that the product meets design intent. Level three is again a subset of level two and represents measurement points that will be used for product prove-out during the ramp phase of product. Level four points are the subset of level three points that establish Process Control Points monitored during production. If problems occur with the part or measurement data during production, measurements will revert back to lower level measurement point until the problem is corrected. Level five measurements focus on features rather than specific points. These measurements are chosen such that they indicate variation in each operation of the manufacturing or assembly process with the use of simple tools or go/no-go gages. Level five measurements allow the operators to assess products in real time and to stop production if something goes wrong.

Locators are defined for dimensional management of parts during production. Dimensional Management uses locators and measurement points to accurately and repeatedly positioning parts during manufacturing and assembly. Locators have three defined configurations: surfaces, holes/pins and edges. The dimensional management practices require locators to be defined for all parts to help control the six degrees of freedom.

4.2.2 Overview of the VRM Process

The VRM processes used at the Ford Motor Company can be divided into four areas of discussion. These four areas are Product and Process Design Activities, Production Control Activities, Dimensional Management Responsibilities and External Supplier Requirements. For the purpose of the VRM Process overview, each of these areas are discussed individually.

4.2.2.1 Product and Process Design Activities

Use of the Failure Modes and Effects Analysis (FMEA) is the primary means for identification, assessment and mitigation of Special Characteristics. FMEA is a technique that identifies potential failure modes and their causes. FMEA systematically identifies and assesses potential failures. Characteristics are considered for both product and process with the use of separate Design and Process FMEAs. The development process requires product design and production process to be coordinated. This ensures concurrent development allowing for tradeoffs to be made on a continuous basis.

Six levels of FMEAs are performed throughout the development process. Four Design FMEAs focus on the product design: concept, system, sub-system and component level. Two remaining Process FMEAs consider the manufacturing and assembly processes. The entire FMEA process starts with the System Design Requirements. These requirements feed the Design FMEA where Critical and Significant Characteristics are designed out to achieve robustness, if it is possible. The Process FMEA is concurrently performed to find additional Special Characteristics. As with design, alternative processes are considered to avoid the Special Characteristics. All FMEAs are considered continuous processes or working documents throughout the development. In most cases FMEAs are not formally completed, but are continually reviewed to identify and resolve special characteristics. The primary objective for application of FMEA is identify problems and remove them while the design is still in paper form.

Ford Motor Company believes concurrent development of the product and process is what makes VRM and product development processes very effective. In normal circumstances final selection of Special Characteristics have to at least be approved by Manufacturing Engineering.

This forces Product Engineering and Manufacturing Engineering to discuss the design and process to ensure integration. If problems exist, it becomes the designer's responsibility to work with manufacturing to identify an alternative to resolve the Special Characteristics. If all avenues are exhausted and no reasonable alternatives are found, then a Special Characteristic can be designated to drive the control plan. If Product Engineering and Manufacturing Engineering can not come to agreement on identified problems, designers can override Manufacturing Engineering to get the characteristic designated. However, Product Engineering must carry the cost of the added control measures.

Interviews have revealed Design and Process FMEAs are consistently used to support VRM activities. For most new developments FMEA information will be reused to the extent possible. FMEA results are generally updated or revised only when the design has been changed. Recent development of the Advance Vehicle Technology (AVT) database is expected to help leverage and increase the distribution of FMEA information between developments. At the time of the interviews, this database was only partially populated and not fully implemented.

4.2.2.2 Production Control Activities

Production Control Activities related to VRM focus around the Dynamic Control Plan (DCP) process. Ford Powertrain Procedure defines DCP as follows:

> *Dynamic Control Planning is a process that links quality tools to build robust control plans. It strategically uses elements like flow charts, FMEAs, and control plans together, rather than separately, in a whole system approach to process planning. Quality, analysis, and planning tools are used, along with team experience, to produce a cohesive system of knowledge. Process controls are developed from this cohesive system of knowledge.*

DCP is required by Ford Automotive Operations to be used as a standard for completing in-station process controls.

This DCP process is structured around ten steps. The first step is to initiate the process through proper resource allocation. DCP is required by Advanced Product Planning Requirements APQP to start in early design phases, overlapping product design. The second step is to define a team structure used to support the process. On some developments the DCP team will also act as the Advanced Product Planning Team; when this is not the case, teams are required to work together. DCP teams will be a cross-functional group with 4-10 members generally including a Facilitator, Product Engineer, Process Engineer, Manufacturing Representative, Product Suppliers and Product Customers.

The remaining eight steps are activities that must be performed through coordinated DCP team efforts. These activities start with step three, which initiates a Question Log. This Question Log is used to coordinate team activities, record open questions, issues and concerns, capture ideas for future consideration, track progress and record acquired knowledge. Step four will focus on collecting the required supporting information, which will include product development information, existing product and process information and similar product and/or process information. Considered most important, step five will be used to develop Process Flow Charts and Product-Process Linking Techniques (i.e., Characteristic Matrix, Correlation Matrix, DOE, etc.). The Process Flow Chart will define all process operations, process outcomes and potential sources of variation. The Product-Process Linking Techniques will be used to define linkages that exist between all operations and product characteristics.

The remaining steps of the control process define control requirements. Defining the control processes begins with step six, which will define pre-launch or preliminary process controls. This will help identify existing process controls and determine additional controls for the new product/process. Step seven involves the Process FMEA, that will involve reviewing existing FMEAs or to complete one for new or changed processes. Step eight will be used to define the control plan. Step nine develops control plans, illustrations and instructions. The final step is to implement and maintain the defined control plan.

Interviews have indicated that DCP has proven to be a very useful process for organizing the efforts required in developing an effective control plan. DCP has been applied to a number of

new and existing product lines to help avoid and/or reduce problems in production. Globalization of DCP was initiated in 1995 and it has been fairly well received on most developments. Complete and consistent use of the process for all developments is being achieved as existing product lines are replaced with new developments.

4.2.2.3 Dimensional Management Responsibilities

Dimensional management responsibilities are focused by the Total Vehicle Dimensional Control Discipline (TVDCD). Efforts of Dimensional Management group are used to manage dimensional related characteristics primarily for body structures, as well as, subassembly and installation of interior trim, exterior ornamentation, and chassis components. This discipline allows Ford to achieve a level of process capability and repeatability that reduces dependence on operator finesse or interventions in production. TVDCD is achieved through a series of variation reduction activities coordinated between design, manufacturing and assembly functions. These management activities are accomplished by identifying and controlling Significant Features. Proper manufacturing and assembly of these features is ensured through careful selection and monitoring of part locators and measurement points.

Dimensional Variation Analysis (DVA) is the primary method used by the Dimensional Management group supporting VRM. DVA is the study of dimensional variation for given designs that occur during component manufacturing and vehicle assembly or subassembly; it considers effects of variation on the total vehicle dimensional characteristics. There are several techniques that can be used to accomplish DVA. Limit stacks, Root Sum Square (RSS) and computer modeling software (i.e., Variation Simulation Analysis and others) are the primary methods used.

Application of DVA is generally performed through six defined steps. The first step is to define a dimensional management team. Step two is used to establish locators. In many situations locators are selected based on surrogate information from previous products, processes and/or statistical data. Step three identifies Significant Features that must be monitored. Step four is used to establish a preliminary assembly sequence. Based on locator information and assembly

sequences, step five constructs a DVA computer model. This model will be used simulate the variation from the material, manufacturing and assembly variations. The final step is to evaluate the analysis results and determine corrective actions. Corrective actions will generally fall into one of four categories. These categories are to change product design, change manufacturing/assembly processes, change both the product and process designs or change vehicle specifications.

Based on interviews, activities of Dimensional Management have provided several noticeable improvements toward the development of quality products. Establishing a consistent process for managing dimensional characteristics is one area of improvement. Another area is smoother product launches. Early involvement and coordination of dimensional characteristics has helped resolve many problems before the product is in production; this has helped reduce the overall time required for ramp. Product development cycles have also been reduced due to consistent application of dimensional management practices between developments.

4.2.2.4 External Supplier Requirements

External supplier requirements are outlined in a series of documents jointly developed between Chrysler, Ford and General Motors. The development of these manuals stems from formation of the Automotive Industry Action Group (AIAG). This group was established to standardize the reference manuals, procedures, reporting formats and technical nomenclature used between these three companies. Requirements placed on the external supplier are outlined in Advanced Product Quality Planning and Control Plan (APQP), Production Part Approval Process (PPAP), and Quality System Requirements (QS-9000) manuals. Supplemental instructions to these primary requirements are detailed in the Statistical Process Control (SPC), Measurement System Analysis (MSA) and Potential Failure Mode and Effects Analysis (FMEA) manuals.

The Advanced Product Quality Planning and Control Plan manual defines requirements for VRM and product development activities. Included in the manual are recommended tools and techniques used in conjunction with VRM. The primary recommended tools are Design and Process FMEAs; this process is discussed extensively earlier in this chapter. Other supporting

processes include development of process control plans and flow charts, review of historical warranty and quality information, interaction of cross functional teams, benchmarking of products and processes, studies of product reliability, use of design for manufacturing and assembly and several others process of this type. Combined application of these processes helps to produce a product quality plan that minimizes the impact of characteristic variation.

Additional requirements placed on external suppliers are defined in the Production Part Approval Process and Quality System Requirements manuals. The Production Part Approval Process will determine if the supplier properly understands engineering design records and specification requirements. PPAP also ensures that suppliers have potential to produce a product meeting these requirements at required production rates. The purpose of Quality System Requirements is to define fundamental quality system expectations for production of service parts and materials.

Interviews have revealed that requirements placed on external suppliers encourage application of VRM, however, many VRM activities are performed independent of internal activities. Coordination between internal and external organization functions is achieved through design reviews. Furthermore, there are deviations in application of VRM processes. In most cases suppliers are allowed to use tools and techniques of their choice as long as it satisfies overall compliance requirements.

4.3 Details of the Assessment

In Chapter 2 the basis for individual company assessments is defined. In this section the Ford's process is compared to the assessment baseline. For each of the VRM activities and requirements, a brief statement indicates if and/or how the requirement is met. In addition, a subjective rating (good, moderate or poor) is given for each VRM requirement in the second part of the assessment.

4.3.1 VRM Activities

1. **Identification activities (product-focused)** start with the identification of system requirements and flow them down to detailed parts. The flowup and flowdown procedures ensure that the system KCs(s), sub-system KCs and feature level KCs are systematically identified and their relationships explicitly captured.

Supporting Practices:

- Design and Process FMEAs evaluate specific product levels for potential KCs. Evaluated levels include product, system, sub-system, component and process (manufacturing and assembly).
- Process Flow Charts and Product-Process Linking Techniques are developed during DCP activities to illustrate relationships between product levels based on manufacturing and assembly processes. These tools help to identify product levels or production stages where variation originates, becomes apparent or can be altered.
- QFD is used on some developments to flow down customer requirements.

Potential Problems:

- FMEAs do not support clear traceability of KCs. During the FMEA, product levels are often evaluated independent of one another.

2. **Assessment activities (product-focused)** use the KC flowdown along with cost and capability data to identify KCs at a high risk (either a high probability of occurring and/or high cost of failure).

Supporting Practices:

- Design and Process FMEAs are the primary methods used to assess KCs. Product, system, sub-system, component and process (manufacturing and assembly) levels are all assessed with separate FMEAs.
- Cross-Functional Teams and Team Structures are use to support assessment activities.
- During the DCP activities, Process Flow Charts and Product-Process Linking Techniques assess KCs for the production process.
- Dimensional Management uses DVA/VSA to evaluate dimensional variation. This analysis is based on design and assembly sequences for the product from individual parts through complete assemblies.
- Preliminary Process Capability Studies assess major systems, subsystems and components for expected variation.
- Product/Process Benchmarking Data is used to assess various components, subsystems and systems for Product/Process Design.

Potential Problems:

- The sole use of FMEAs does not adequately support traceability of KC information or KC flowdowns required to support assessment.

- Limited modeling and quantitative analysis determine variation impacts. (Dimensional Management is the exception). It has been noted that efforts are being focused on improving the use of models for variation analysis.

3. **Mitigation activities (product-focused)** identify and select the best process for reducing the impact of variation. There are four alternatives that can be implemented separately or together: design changes, process changes, control/measurement, and process variation reduction.

Supporting Practices:

- Results from Design and Process FMEAs guide mitigation activities. These mitigation activities will address the component, subsystem, and system levels individually.
- Dimensional Management uses DVA/VSA to evaluate mitigation alternatives through continued modeling of selected alternatives (tolerances and/or nominal values).
- The DCP team uses the Product-Process Linking Techniques to guide selection of mitigation strategies. These mitigation activities are focused primarily on production processes.
- A Feasibility Commitment Review requires Product Quality Planning Teams to assess the feasibility of designs and supporting production processes, which include control strategies. Special attention is given to management of designated characteristics.

Potential Problems:

- Interviews have revealed that there are often too many measurement points selected for the allocated control resources. Some are redundant measurements placed at multiple product levels, because KC relationships/KC flowdowns are not clearly defined or understood.

4. **Documentation and Communication activities** support the capture and transfer of VRM information. In addition, these documents capture reuse/legacy information.

Supporting Practices:

- FMEAs are the primary tools used for documenting and communicating KCs during design activities.
- Process Flow Charts and Product-Process Linking Techniques document and communicate VRM information related to production processes.
- Checklists document and communicate VRM information that must be addressed throughout development processes. Included in these documents are the Control Plan, Production/Process Quality, Design Information, Design and Process FMEAs and Process Flow Chart checklists.
- Working Data Sheets are used to document and communicate VRM information specific to DCP activities. This sheet is used to manage preliminary process control information.

Potential Problems:

- Interviews have indicated that coordination of centralized VRM documentation has not yet been achieved. In some situations, duplicate systems have been noted to exist.
- Interviews have revealed that external suppliers do not consistently follow activities outlined in AAIG manuals. This has made it difficult to ensure VRM information is consistently documented and can be consistently exchanged between internal and external organizational functions.
- Interviews have revealed FMEA information for all products is not consistently updated and/or maintained in a central location. The AVT database is under development to help resolve this problem.

5. **Identification activities (organization-focused)** require organizational functions (including suppliers) and CFTs to perform and coordinate KC identification.

Supporting Practices:

- Cross-Functional Teams and Team Structures support organizational interactions during Product/Process Design, DCP and Dimensional Management activities.
- During DCP, Question Logs encourage and coordinate communication with other organizational functions.
- Development of Design/Process FMEA is required to be a Cross-Functional activity.
- QFD is performed on some developments to flowdown customer requirements. This activity supports interactions between customers and other organizational functions.

Potential Problems:

- Interviews have indicated a number of separate identification activities are being performed, but they are not always coordinated. Product/Process Design, DCP and Dimensional Management all perform individual identification activities with only limited coordination.

6. **Assessment activities (organization-focused)** require cross-organizational efforts. Of the three VRM stages, assessment requires the most amount of cross-organizational coordination. Assessment requires input from and coordination between multiple organizational functions to accurately consider the risk of KCs. Risk, as defined above, is a combination of the cost of a failure (set by the design organization) and the potential for that failure (set by the manufacturing process).

Supporting Practices:

- Cross-Functional Teams coordinate assessment activities between organizational functions during Product/Process Design, DCP activities and Dimensional Management.
- Dimensional Management groups require representatives from Design, Manufacturing and Assembly to participate in all assessment activities.
- Development of Design and Process FMEAs is required to be a Cross-Functional activity.

Potential Problems:

- Because there are no clear links between Design and Process FMEA, these reports tend to be developed independent of one another. In some situations these FMEAs are developed by separate functions or teams. Coordination of information between these FMEAs becomes highly dependent on organizational interaction; interviews have indicated that these interactions are not consistently maintained.

7. **Mitigation activities (organized-focused)** require collaboration between multiple organizations to select effective mitigation alternatives. All mitigation alternatives should be selected based on a collaborative decision that considers the overall product.

Supporting Practices:

- All Control Plans that include Special Characteristics must be approved by Product Engineering and Process Engineering Members, Manufacturing and Quality Members, Union Team Members or equivalent Product Personnel, Customers and others, as appropriate.
- Development of Process Control Plan is required to be a cross-functional activity.
- Final selection of mitigation alternatives for Dimensional Management requires Design, Manufacturing and Assembly approval.

Potential Problems:

- Interviews have revealed that interactions between Product Engineering and Manufacturing Engineering, prior to release into production, are not always consistent.
- Interviews have indicated that mitigation activities are not well coordinated between Product/Process Design, DCP and Dimensional Management activities.
- Interviews have revealed that coordination with external suppliers is not consistent during mitigation activities.

4.3.2 VRM Requirements

Identification

1. **KCs must be identified at each product level (i.e., system-level, sub-system level, and feature-level).** *(Good)*

   Design FMEAs support review of product, system, sub-system and component levels. Process FMEAs evaluate manufacturing and assembly activities.

2. **Identification must be shared and coordinated among organizational functions and CFTs.** *(Good)*

   Cross-Functional Teams and individual Organizational Functions use FMEA to perform identification.

3. **The KC flowdown must capture both individual KCs as well as relationships between them.** *(Moderate)*

FMEA analysis does not accurately reflect relationships between KCs. Occasional use of a Fault Tree Analysis does partially support this requirement, but it is generally used for problem solving. Use of Process Flow Charts and Product-Process Linking Techniques for DCP activities identifies relationships, but primarily between product characteristics and production processes.

4. **The identification process must result in a set of documents that contain supporting information for assessment and mitigation.** *(Good)*

   FMEA reports are a common format used to support identification information. Process Flow Charts and Product-Process Linking Techniques are used by DCP to supplement Process FMEA reports.

5. **Both functional and dimensional parameters must be evaluated for potential KCs during identification.** *(Good)*

   Design and Process FMEAs identify both functional and dimensional driven KCs.

6. **Identification must be linked to and motivated by customer requirements (internal or external).** *(Good)*

   Preliminary Listing of Special Product and Process Characteristics is used to communicate customer requirements. QFD is also occasionally used to flowdown customer requirements. This requirement is also supported by Customer Driven Vehicle Reports (CDVR) used by Dimensional Management.

7. **Identification activities should occur throughout all development phases.** *(Good)*

   All FMEAs are intended to be working documents throughout the development. This requires Cross-Functional Teams to continually consider products and processes for potential KCs.

8. **Identification should consider New Technology as a source for potential KCs.** *(Good)*

   Interviews have indicated that extensive evaluation of New Technology is performed before it is released into new designs. FMEAs, Cost Models, Produceability Studies and Benchmarking Studies are all required to be performed for New Technology.

Assessment

1. **Assessments should consider individual feature variation and the impact of feature variation on system requirements using KC flowdowns.** *(Good)*

   FMEAs are performed for product, system, subsystem, and component levels, however, there is very limited traceability to system requirements or between these levels. DPC activities use Process Flow Chart and Product-Process Linking Techniques to consider the impact of production process variation. DVA is used by Dimensional Management to consider the impact of feature variation on final assemblies.

2. **Assessment activities must be shared and coordinated among organizational functions and CFTs.** *(Moderate)*

   Cross-Functional Teams ensure information is obtained for assessment activities. However, interviews have revealed inputs are not consistently obtained during assessment.

3. **Information/documentation from assessment activities must be maintained and accessible.** *(Good)*

   FMEA reports are a common format used to document and communicate assessment information. Process Flow Chart and Product-Process Linking Techniques supplement FMEA reports for DCP activities. A High-

Medium-Low (HML) Contributors Report is generated from DVA tools, providing a standard form for Dimensional Management. Additional forms include Preliminary Process Capability Study, Measurement System Analysis, Product Benchmarking, Design Verification and Product Reliability reports.

4. **Assessment must be used to validate potential KCs before they are considered for mitigation.** *(Good)*

   FMEA is used for validation based on the severity, occurrence and detection of the individual or the combined total Risk Priority Number (RPN), however, most FMEA information is qualitative. Dimensional Management uses the High-Medium-Low (HML) Contributors Report as a basis for validation.

5. **Assessments of robustness should be based on quantitative measures through use of hardware, analytic models and/or computational systems.** *(Moderate)*

   Interviews showed limited use of models during Product/Process Design activities. Prototype Models are used, but generally late in the design process. FEAs, DOEs, Simulations and Analytical Models are used, but generally on a limited basis. For Dimensional Management, VSA is used consistently to meet this requirement.

6. **Assessment should measure the impact of dimensional variation on functional performance.** *(Good)*

   Based on interviews, FMEAs consider the impact of dimensional variation on functional performance.

7. **Assessment should use process capability feedback information for the analysis whenever possible.** *(Moderate)*

   Interviews have indicated that use of capability feedback is not consistent on all developments. However, a Global Process Capability Database is currently under development to help increase the use of this information.

8. **Assessment should prioritize validated KCs to ensure proper application of mitigation alternatives.** *(Moderate)*

   The distinction between Critical and Significant Characteristics is the primary means by which KCs are prioritized. Critical Characteristics are given highest priority in design and production; Significant Characteristics are second highest. The FMEA results provide a qualitative prioritization of KCs. In Dimension Management, results from DVA will provide a quantitative prioritization of KCs.

Mitigation

1. **Mitigation activities must consider the impact of mitigation alternatives on the overall product.** *(Moderate)*

   Because FMEAs are generated and evaluated for product, system, subsystem and component levels independently they do not consistently reveal variation impacts to the overall product. Dimensional Management does consider overall product impacts using DVA/VSA.

2. **Mitigation must be a collaborative decision between multiple organizational functions (internal and external).** *(Moderate)*

   The Ford Production System requires CFTs to develop Control Plans and obtain approval from all involved Organizational Functions. Interviews have indicated this requirement does not always ensure decisions are collaborative, because control plans only need to be approved by most functions.

3. **Mitigation activities and decisions should be documented.** *(Good)*

FMEAs reports and Control Plans are the primary tools for capturing information from mitigation. The AVT database is intended to further support the communication of FMEA information, however, this database has not been fully implemented. Additional supporting documents include the Pre-Launch and Production Control Plans, Control Plan Special Characteristics Worksheets and Production Part Approval Process reports.

4. **Mitigation activities must be prioritized according to the risk of KCs.** *(Moderate)*

   Prioritization is primarily based on regulatory/safety (Critical Characteristics) versus customer driven (Significant Characteristics) requirements. In other situations prioritization will be determined from the RPN number resulting from FMEAs; this is generally a qualitative prioritization.

5. **Mitigation should select alternatives that support robust designs helping to minimize the total number of KCs needing controlled in production.** *(Moderate)*

   Robust Design does not appear to be directly supported by FPS or VRM process requirements. Techniques like DOE, DFM, DFA and Benchmarking do, however, help encourage robust designs.

6. **The selection of a mitigation strategy should be based on the cost and cost benefit data.** *(Moderate)*

   Based on interviews cost data is not always considered during mitigation of CCs and SCs. This is especially true for Critical Characteristics, which tend to be controlled at any cost. Interviews have indicated that Control Plans or Measurement Plans are generally based on cost data to ensure cost-effective control measures.

Documentation and Communication

1. **Documentation and Communication must support the exchange of information throughout and between developments, between organizations and throughout VRM stages (identification, assessment, and mitigation).** *(Moderate)*

   FMEA reports and Control Plans are common and consistent forms for exchanging VRM information. Development of the AVT database was intended to further support exchange of FMEA information. Supplemental Documentation that supports this requirement include QFD (1st and 2nd levels), Production Part Approval Process Documentation, Process Flow Charts, Product-Process Linking Techniques, Design Verification/Validation Plans and Reports, Control Plan Special Characteristics Worksheets, Checklists and the Working Data Sheets.

2. **Documentation and Communication must support flowdown and traceability of requirements for KC information.** *(Moderate)*

   VRM information flowdown is performed through DFMEA, PFMEA and Control Plans. Interviews and documentation have revealed that traceability of information specific to KCs is not well maintained. Also, there is no method that supports a flowdown specific to KCs.

3. **Documentation and Communication must support process capability feedback for identification, assessment and mitigation functions.** *(Moderate)*

   Interviews have revealed that a Global Process Capability Database is being constructed to improve documentation and communication of this information. However, up to this time process capability information has not been consistently captured or exchanged.

4. **Documentation and Communication must capture information necessary for reuse/legacy data.** *(Good)*

Current product/process design activities reuse all FMEA information for designs that have not changed. The AVT database has been developed specifically to support exchange of FMEA information, which supports this reuse requirement. For Dimensional Management, surrogate information is consistently used to establish locators, measurement points and determine statistical data for typical or existing designs. During DCP activities, existing measurement and control processes are reused to the extent possible.

5. **Documentation and Communication must provide information necessary for measurement and inspection plans.** *(Moderate)*

   Design and Process FMEAs are intended to identify characteristics that must be controlled during production. Interviews have revealed that in many situations there is poor alignment between FMEAs and Control Plans; this is partially compensated for by requiring both Design and Manufacturing to signoff on control plans.

Documentation Instructions

1. **Documented instructions must have clearly defined goals and objectives for VRM.** *(Moderate)*

   Based on the documented material, there are goals and objectives defined for individual processes supporting VRM. However, there are no clear goals and objectives specific to VRM.

2. **Documented instructions must provide sufficient training and supporting process material.** *(Moderate)*

   There are well-documented instructions for individual processes that support VRM, but very few documents exist to outline the overall VRM process.

3. **Documented instructions must ensure a consistent set of definitions and/or classifications is established and used.** *(Moderate)*

   Documentation and interviews have revealed that there are deviations in the definitions and/or classifications of KCs across organizational functions. In some situations, organizational functions have elected to expand KC definition/classification for their own use. However, Special Characteristics (Critical and Significant Characteristics) are consistently recognized by all internal and external organizational functions.

4. **Documented instructions should communicate the activities required when a KC is identified. This ensures that all organizational functions are aware of the consequences and/or reactive measures that result from a KC classification.** *(Good)*

   Expected reactions and implications for KCs are outlined in the Advanced Product Quality Planning (APQP), Production Part Approval Process (PPAP) and Quality System Requirement (QS-9000) manuals. These requirements are also outlined in supplemental documentation that has been developed specifically for KCs.

4.4 Assessment Summary

The assessment of Ford's VRM process satisfies many of the VRM requirements but there are still several gaps. The following discussion summarizes these findings.

4.4.1 Supported Activities and Requirements

Design and Process FMEAs are the primary tools for accomplishing VRM at Ford Motor Company. Concurrent development of FMEAs support identification and assessment of nearly all controlled KCs. All FMEAs are reused for designs that have not changed. The FMEA results are reviewed during development of Control Plans, helping to tie together mitigation to identification and assessment functions. FMEAs and Control Plans both provide a standard form to exchange information specific to VRM. Extensive documentation exists to ensure proper execution of these processes and to support all required training. Included in this documentation are AAIG manuals, which outline all recommended VRM procedures for both internal and external organizational functions.

The Dynamic Control Plan process uses a CFT to develop Control Plans that clearly support VRM objectives. This process outlines a set of procedures that help to minimize and control the impact of variation resulting from production processes. DCP relies heavily on the development and use of Process Flow Charts and Product-Process Linking Techniques. These charts and matrix help ensure that each process operation is evaluated for potential variation and potential impact to all Special Characteristics.

The Dimensional Management group is used to provide specific emphasis on dimensional variation. This group uses VSA Models to model variation of design, manufacturing and assembly parameters. Assessments are almost always quantitatively based and mitigation alternatives require collaborative decisions with Design, Manufacturing and Assembly. This analysis is applied to subassembly and installation of metal parts, trim, ornamentation and chassis parts. Coordinated selection of Special Features, Locators and Measurement Points support control and monitoring of part variation during manufacturing and assembly processes.

4.4.2 Unsupported Activities and Requirements

The lack of a clear KC flowdown is the most significant problem with Ford's VRM process. Even though FMEAs are consistently applied to product, system, subsystem, component and process levels, there is only limited connection between FMEA analyses. As a result, Special

Characteristics tend to be identified, assessed and mitigated individually, rather than from an integrated product perspective. Without a clear KC flowdown it is very difficult to determine the impact of variation to the overall product. It is also difficult to identify all sources of variation or percent contribution of each variation source. A KC flowdown is useful to help tie together Design FMEAs, Process FMEAs and Control Plans. The flowdown will help define all points or levels in the product where variation will originate, be observed, be altered or can be controlled.

Limited coordination between individual VRM activities reduce the effectiveness of the VRM execution. VRM activities are currently divided between Product/Process Design, DCP, Dimensional Management and External Suppliers. Interviews have revealed that coordination between these groups is not consistent. It was also revealed that each group tends to maintain a set of VRM documentation not made readily available to all groups. This divided approach to VRM does not support the most effective execution of assessment and mitigation activities. Assessments can often be redundant and information is not consistently shared to ensure adequate assessment. Additionally, mitigation alternatives are not always based on collaborative decisions, reducing optimal selection for the overall product or process.

5 Assessment of Xerox's VRM Process

5.1 Chapter Introduction

This chapter provides an overview and assessment of variation risk management activities for Xerox Corporation. The chapter is presented in three parts: a general overview of KC definitions and classifications and VRM processes; an assessment of current practices; and a summary.

5.2 General Process Overview

The following three sections identify benefits and shortcomings of Xerox's VRM practices. The assessment is based on Xerox's documented material for Critical Parameter Management (CPM). Because application of CPM varies across divisions, the analysis is based on a combination of documented materials and Xerox employee interviews.

Xerox Corporation produces small to medium scale document management and reproduction systems. This product is considered moderate to high in design complexity and produced in low to high volumes. Most are designed or redesigned jointly between internal teams and external suppliers who have both design and production responsibility.

Interviews upon which this evaluation is based were performed through on-site visits and off-site discussions. The following manuals were referenced:

Time to Market Core Process, Release 2.0, May 2, 1997

Critical Parameters Workshop, BEW0226, February 1997

Engineering Excellence Hardware Fundamentals Workshop, Objectives, Revision #002, August 1996

Engineering Excellence Hardware Fundamentals Workshop, Critical Parameter Management, Revision #003, 1996

Engineering Excellence Hardware Fundamentals Workshop, Technology Readiness Process, Revision #004, July1996

Low Cost Delivery Unit Design Quality and Critical Parameter Management, A2-97 Technical Program Office, April 2, 1997

Engineering Excellence Hardware Fundamentals Workshop, Integrated System Design, Revision #003, April 1997

5.2.1 Classifications and Definitions of KCs

Xerox identifies their Key Characteristics as Critical Parameters (CPs) at functional levels and Critical Specifications (CSs) at detailed-part/manufacturing levels. Critical Parameters are defined as measurable design variables that directly affect the performance of a system/subsystem. They are variables identified as vital or critical to the function of their design, and therefore must be controlled to ensure proper functionality. At the higher design levels, CPs are focused on functional performance rather than specific form and fit issues. As a result, Critical Parameters commonly associated with forces, positions, temperatures, charge, times, etc., are built up from parts, dimensions and components. All identified Critical Parameters must have defined nominal values and tolerances. All Critical Parameter processes are required to be in statistical control and meet the criteria of a Cpk $\geq \underline{1.00}$ with 95% confidence[16].

Critical Parameters are enabled by Critical Specifications identified at part, component or subassembly levels. Critical Specifications are defined as the most important component requirements expressed on engineering drawings. It is common for several Critical Specifications to be required to ensure control of a single Critical Parameter. Relationships between Critical Parameters and Critical Specifications must be represented using Input/Output/Constraint (IOC) Charts[17], Functional Analysis System Technique (FAST)

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[16] The confidence interval is an uncertainty estimate that considers the number of samples used to determine a Cpk number. The index requires higher Cpk values for smaller sample groups.

[17] The Input/Output/Constraint Chart is developed for the decomposed functional elements of a design. An IOC chart is a document that captures current design knowledge about energy (or information) input and output. The Chart is used to list the functional inputs, dysfunctional inputs, design constraints from earlier decisions, intended outputs, and unintended outputs for the represented system or subsystem.

diagrams[18], and/or a Quality Functional Deployment (QFD) flowdown. A database, referred to as SEDIR[19], is used to manage relationships between IOC charts for multiple product systems providing an integrated system. All Critical Specifications are to be controlled by manufacturing processes, to the extent possible. Critical Specification processes must also be in statistical control and demonstrate a Cpk $\geq$ 1.33 with 95% confidence. All Critical Parameters and Critical Specifications that do not meet defined criteria can not be accepted without an appropriate performance waiver. This waiver must be obtained through Design Engineering and signed by Program/Product Managers.

5.2.2 VRM Process Overview

The overarching philosophy to Xerox's Variation Risk Management process is Critical Parameter Management (CPM), which has been defined as follows:

> *Managing the commercialization of a technology or design via the systematic application of the Critical Parameter Development and Implementation processes. Management has to continuously ensure that the process is followed and the maturity of the design & manufacturing process is tracked via certification of Critical Parameters at the subsystem & system level.*

Critical Parameter Management identifies two separate stages. These stages are Critical Parameter Development (CPD) and Critical Parameter Implementation (CPI), which are defined as follows:

> *Critical Parameter Development: Identifying and Quantifying the technology requirements (Critical Parameters) of a subsystem/system to achieve the specified performance outputs (responses), for given inputs and constraints, under all*

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[18] The FAST diagram is similar to a KC Tree. This diagram is used as a graphical representation of the logical relationships between system level performance requirements and detailed-level characteristics. These diagrams will show the CP flowdown, through product levels, to CSs.

[19] SEDIR is an acronym for Systems Engineering Design Information Repository.

accepted conditions (noise factors). Initiating the certification on the Critical Parameters (CP) by validating their nominals and latitudes using Robust Design Techniques.

Critical Parameter Implementation: Translating the Critical Parameters into engineering drawing specifications (Critical Specifications). Certifying the product design using process qualification of selected design Critical Parameters and manufacturing process Critical Parameters(CP) and all Critical Specifications (CS).

Critical Parameter Development and Implementation are continuous, iterative processes that evaluate the overall product throughout the development process. CPD is divided into seven major steps. Step one defines Inputs/Output/Constraint Charts and performs initial CP definition for addressed systems or subsystems. Step two performs experimental preparation and modeling analysis. Step three assesses preliminary manufacturing processes based on expected production methods. Step four is required when experimental hardware is required, such as in situations where analytical models do not exist or are not sufficient for analysis. Hardware is always required for verification testing or model validation work. If necessary, step four is used to build and audit experimental hardware. CPD requires use of experimental/actual hardware or analytical models to be used for system assessments. Step five focuses on determining design nominals through optimization and verification with the use of hardware, model and Robust Design. With the nominals defined, step six is required to define and validate ranges (tolerance) for all identified CPs. The final step completes this cycle by updating drawings and documentation with identified requirements for CPs.

Critical Parameter Implementation closes the loop on Critical Parameter Development. Primary emphasis is to identify, assess and mitigate Critical Specifications necessary to support Critical Parameters. CPI is divided into six steps. Step one is to collect design outputs, which can include CPD outputs, preliminary product designs, preliminary manufacturing assessments, selected suppliers, potential CSs and other information required to perform CPI activities. Step two is used to define piece-part/detail-level Critical Specifications; this step involves defining

nominal values and tolerances for CSs and then comparing them to CPs to ensure they meet system-level performance requirements. Step three transfers confirmed CS nominal values and tolerances to specific parts and assemblies to confirm the process capability. Step four is used to confirm the capability for each subsystem. Design will flow back required changes to detail part requirements defined in step three. With subsystem capability confirmed, step five is used to confirm capability at the system level; any required changes will require repeating earlier CPI steps. The final step is used to verify process capability for both CPs and CSs and establish continued monitoring requirements for production.

The effectiveness of CPM is increased with the concurrent use of Engineering Excellence Fundamentals. Engineering Excellence Fundamentals are a collection of practices and methodologies that support the Xerox's Corporate-level objectives of customer-focused, quality products delivered at minimized cycle times. Included in these fundamentals are guidelines for Quality Functional Deployment, Integrated System Design, Reusability, Robust Design, Technology Readiness, Product Quality and the Critical Parameter Management process. CPM requires use of Robust Design to define best nominal values and hardware functional tolerances. The remaining design practices are an integral part of CPM used to help support overall VRM goals and objectives. For example, QFD is used to flow down system-level/customer requirements to product levels for CPM application. Integrated System Design is used to help coordinate interfaces between system and subsystems.

Interviews have revealed execution of CPM is fairly consistent across most developments. This process is well documented. Required training helps to ensure individuals and teams are aware of CPM and apply the process according to stated requirements. Execution of VRM is also supported indirectly through required activities and outputs defined in the product development process; these are outlined in the next section. Based on interviews, documented VRM procedures are a reasonable representation of the performed activities with only a few exceptions between developments.

5.2.3 Overview of the Product Development Process

Control of Xerox's product development process is clearly outlined in Time to Market (TTM) Core Process Definitions. This manual defines all required activities during development of all products. The overall structure of TTM ensures that developments meet or exceed quality and customer focused objectives for Xerox. Because TTM is used for all products, it creates consistency between generated inputs, outputs and supporting tasks, which include VRM information. This consistent, systematic structure of TTM allows retention of information and knowledge, leveraging it from one development to another. From the perspective of effective use of VRM, all identified tools and techniques supporting VRM are coordinated and/or scheduled through TTM process requirements.

Although the TTM Core Process is primarily focused on activities of internal organizational functions, external suppliers are expected to consider and be aware of many of these requirements. Continuous Supplier Involvement (CSI) process manages suppliers responsible for delivering parts, components or assemblies, that require significant process development. CSI is an integrated part of TTM requiring all key suppliers to become involved early in the development. TTM requires suppliers to follow Engineering Excellence Fundamental practices, including the Critical Parameter Management process. TTM and CSI require Design Engineering and Product Teams to ensure suppliers understand relevant Critical Parameters and Specifications. The supplier is responsible for providing a plan to control and monitor all identified critical items. Product Teams must work through control details with suppliers to ensure quality standards will be meet.

5.3 Details of the Assessment

In Chapter 2 the baseline for the individual company assessments is defined. In this section Xerox's process is compared to the assessment baseline. For each of the VRM activities and requirements, a brief statement indicates if and/or how they are met. In addition, a subject rating (good, moderate or poor) is given for the VRM requirements in the second portion of the assessment.

5.3.1 VRM Activities

1. **Identification activities (product-focused)** start with the identification of system requirements and flow them down to the detailed parts. The flowup and flowdown procedures ensure that the system KCs(s), sub-system KCs and feature level KCs are systematically identified and their relationships explicitly captured.

Supporting Practices:

- Requirements of CPD and CPI processes ensure that each product level is evaluated for CPs and CSs. This is partially accomplished using Functional Analysis System Technique (FAST) diagram. FAST diagram methods will capture relationships between system/subsystem CPs and part-detail/manufacturing-process CSs as they are understood at the time.
- CPM requires use of QFD to identify and flowdown CPs and CSs through the product levels. QFD flowdown starts with a preplanning matrix (Voice of the Customer, Prioritization, Competitive Benchmarking, Strategy), then requires a house to be defined for multiple product levels (i.e., system, modules, subsystems, components, manufacturing parameters). Flowdown ends with a Production and Quality Planning Matrix (MFG. Process Specifications, Prioritization, Process Controls, Tooling Controls, Quality Controls).
- Design and Process FMEAs drive some identification activities. FMEA requires that potential failure modes for all product levels be considered. Identified potential failure modes are further investigated through CPM.
- There is use of Analytical Models and existing data from similar designs.

Potential Problems:

- Interviews have reflected that the QFD flowdown is not consistently executed or completed for all product levels.

2. **Assessment activities (product-focused)** use the KC flowdown along with cost and capability data to identify KCs at a high risk (either a high probability of occurring and/or high cost of failure).

Supporting Practices:

- CPD and CPI have defined steps that require assessment of identified CPs and CSs for systems, modules, subsystems, components, and/or manufacturing parameters.
- FAST diagrams capture relationships between CPs and CSs throughout the product levels. These diagrams can also be used to determine contributions of CSs on CPs, for assessment.

- QFD (individual product-level houses) requires information to be recorded on competitive assessments, test results, specification correlation, technical assessment, technical importance ratings, design robustness and process capability assessments for many of the evaluated product levels.
- Relationships between IOC charts are presented in the form of IOC flowdowns. IOC flowdowns assess potential sources of variation (Dysfunctional Inputs/Outputs) or any misalignments of inputs/outputs/constraints between systems/subsystems.
- Use of System and Subsystem Test Hardware and Analytical Models help to ensure product levels and their interactions are considered.

Potential Problems:

- Interviews have reflected that consistent use of Experimental Hardware and Models throughout assessment activities is highly dependent on resource availability. In some developments sufficient Hardware or Model can not be secured.
- Interviews have indicated that tolerance allocation for typical parameters (Non CPs or CSs) is not always based on design or performance requirements. As a result, the assessment may reflect inconsistent tolerance allocation between product levels rather than the impact of critical parameter variation.

3. **Mitigation activities (product-focused)** identify and select the best process for reducing the impact of variation. There are four alternatives that can be implemented separately or together: design changes, process changes, control/measurement, and process variation reduction.

Supporting Practices:

- Selected Control Plans, Measurement Points, SPC requirements and Design or Process Changes must be based on the identified product level interactions/relationships.
- QFD is used to help define preliminary control requirements through the consecutive flowdown of product level requirements. Use of QFD to flow down product level requirements will end with a Production and Quality Control Planning Matrix.
- Robust Design is an integral part of product development and CPM process and is used to ensure nominal values and tolerance ranges are selected based on design intent, cost, delivery and performance requirements. Robust Design practices include Concept Design, Parameter Design, Tolerance Design and On-line QC Design.
- Integrated System Design approach is used to ensure all systems/subsystems are integrated at important subsystem interfaces. Use of this approach ensures mitigation alternatives are selected considering the overall product.

Potential Problems:

- Interviews have revealed that there are problems in identifying and understanding correlation/interactions between product level parameters. This insufficient understand has reduced the effectiveness of selecting the most effective mitigation alternative.
- Interviews have revealed that QFD is not always completed. As a result, a Production and Quality Control Planning Matrix is not developed, limiting the possibility of QFD supporting mitigation alternative selection or control plan development.

4. **Documentation and Communication activities** support the capture and transfer of VRM information. In addition, these documents capture reuse/legacy information.

Supporting Practices:

- Standardized Documentation exists to capture and exchange VRM information. This documentation includes FAST diagrams, IOC charts, IOC flowdowns, Critical Parameter Tracking Forms, Outline Drawings (drawings with CP and CS listed), Critical Parameter Growth Curves, Product Specification Trees, QFD Flowdown, Critical Parameter Management Plans, Design/Process FMEA, Robust design and P-charts.
- Database systems have been or are being developed to support, capture and exchange VRM information. These systems include Product Archive Documentation, Product Requirements Database, CP Database and SEDIR (IOC chart and system/subsystem relationship database/system).
- Product Design Stability Criteria Guidelines have been established to guide CFTs on minimum product design and performance requirements. These are minimum requirements that must be achieved during product development and CPM activities.

Potential Problems:

- Interviews have indicated that the exchange of CPM information is not always performed in a timely manner. In some situations, this has slowed or prevented proper CPM execution.
- Decisions based on assumptions are not always clearly distinguished from those based on detailed qualitative analysis.

5. **Identification activities (organization-focused)** require organizational functions (including suppliers) and CFTs to perform and coordinate KC identification.

Supporting Practices:

- Program teams and/or CFTs are required to perform and coordinate identification activities throughout the development. Program Teams are put in place for each development phase to support Organizational Interactions during development phases. CFT teams, assigned to individual systems/subsystems, will be coordinated through a Program Team.
- CPM requires all Teams, responsible for systems/subsystems, to ensure IOC charts and FAST diagrams are generated and updated to clearly reflect design requirements. This requirement ensures Organizational

Functions and/or Teams are aware of expected Inputs/Outputs, dysfunctional Inputs/Outputs and constraints for all systems/subsystems.

- Continuous Supplier Involvement is used to ensure early and continuous involvement of key part/assemblies/materials suppliers.
- Design and Process FMEAs are used for some identification evaluations. This requires team interaction during these evaluation activities.

Potential Problems:

- Interviews have indicated that enforcing identification activities for external suppliers is not always achieved. Although Continuous Supplier Involvement is used to support this activity, it does not ensure consistent identification activities are coordinated with all external suppliers.

6. **Assessment activities (organization-focused)** require cross-organizational efforts. Of the three VRM stages, assessment requires the most amount of cross-organizational coordination. Assessment requires input from and coordination between multiple organizational functions to accurately consider the risk of KCs. Risk, as defined above, is a combination of the cost of a failure (set by the design organization) and the potential for that failure (set by the manufacturing process).

Supporting Practices:

- CFTs and CFTs structures are established to coordinate assessment activities for the overall product.
- Continuous Supplier Involvement is used to help ensure early and continuous involvement of key part/assembly/material suppliers throughout assessment activities.
- QFD supports communication of VRM information between Organizational Functions and/or Teams responsible for individual systems/subsystems.
- Robust designs assure low cost, high reliability, readiness for customer usage conditions.
- The SEDIR database has been established to help manage IOC charts and support organizational interactions required to coordinate this information. Communication of IOC charts and relationships between systems/subsystems to the appropriate teams ensures this information is considered during assessment activities.
- A number of Product, Process, and Technology Readiness Assessments/Reviews exchange assessment information with other Teams and/or Organizational Functions.
- A Root Cause Analysis is used in some situations to identify relationships between variation problems and root causes. Results from these analysis are summarized in a Lessons Learned Document and communicated to other Organizational Functions for further or future consideration.

Potential Problems:

- Interviews have revealed that data sharing issues between organizational functions can be slow preventing adequate and timely execution of assessment activities. Often this is because lots of conflicting data is evident, or very little data is collected.
- Interviews have indicated that the QFD flowdown is often based on non-quantitative assessments. These assumptions can have significant influence on assessments of CPs and CSs if the information uncertainty is not effectively communicated.
- Interviews have revealed that coordinating and enforcing CPM with external suppliers is problematic.

7. **Mitigation activities (organized-focused)** require collaboration between multiple organizations to select effective mitigation alternatives. All mitigation alternatives should be selected based on a collaborative decision making process that considers the overall product.

Supporting Practices:

- Integrated System Design approach ensures that the overall system is considered during mitigation. All mitigation alternatives are required to be collaborative decisions between all system/subsystem teams, which are generally overseen by Program Teams.
- A number of Product and Process Design Reviews coordinate and finalize mitigation alternative selection. Final reports from these reviews will be used to communicate results to other Teams and/or Organizational Functions.
- The Production and Quality Control Planning Matrix is the final output for the QFD flowdown. This matrix is intended to communicate Manufacturing Process Specifications, Parameter Prioritization, Process Controls, Tooling Controls and/or Quality Controls that have been flown down through the product levels. When properly executed, this final matrix should reflect inputs of multiple Organizational Function or Teams.
- CPM requires that Process Capability Data (SPC) be recorded and communicated to Program Teams as part of CP/CS certification.
- Continuous Supplier Involvement is used to support mitigation interactions with external suppliers.

Potential Problems:

- Interviews have indicated that selection of mitigation alternatives is not always in the best interest of all organizational functions. This problem is most prominent between internal and external organizational functions.
- Interviews have reflected that QFD development is not always completed. If QFD is not completed the Production and Quality Control Planning Matrix can not be used to support mitigation activities.

5.3.2 VRM Requirements

Identification

1. **KCs must be identified at each product level (i.e., system-level, sub-system level, and feature-level).** *(Good)*

   CPM requirements to development QFD flowdowns, IOC charts (SEDIR) and FAST diagrams support consideration of each product level.

2. **Identification must be shared and coordinated among organizational functions and CFTs.** *(Good)*

   CPI and CPD process are structured such that multiple organizational functions are involved in identification of preliminary CPs or CSs. This is accomplished through use of Program Teams, CFTs and Integrated System Design approach.

3. **The KC flowdown must capture both the individual KCs as well as relationships between them.** *(Good)*

   Use of FAST diagrams and QFD flowdowns support identification of product level relationships. CP certification requirements mandate that the percent contribution of CPs to the primary response (signal/noise and sensitivity) be identified. Interviews have indicated that FAST diagrams are consistently developed, but QFD is not always completed.

4. **The identification process must result in a set of documents that contain the supporting information for assessment and mitigation.** *(Good)*

   Use of FAST diagrams, IOC charts, IOC Flowdown, QFD Flowdowns and CP Tracking Lists standardize the CP information. The SEDIR database also supports this standard.

5. **Both functional and dimensional parameters must be evaluated for potential KCs during identification.** *(Good)*

   Critical Parameter Development is focused on functional performance and uses CPs for functional parameters to be controlled. Critical Parameter Implementation process focuses on dimensional parameters that impact the product while using CS to identify these dimensional parameters. Robust design is used to ensure best nominal values and lowest cost tolerances for downstream.

6. **Identification must be linked to and motivated by customer requirements (internal or external).** *(Good)*

   QFD flowdown, which starts with a Preplanning Matrix, helps to ensure that customer requirements are considered.

7. **Identification activities should occur throughout all development phases.** *(Good)*

   CP or CS identification starts in the early development phases and is continuously performed throughout the product development process. CPM requires continuous evaluation for potential CPs or CSs.

8. **Identification should consider New Technology as a source for potential KCs.** *(Moderate)*

   Technology Capability Demonstration and Assessment requirements help to ensure that New Technology has been evaluated for CPs or CSs and is ready for implementation. Interviews have indicated that in several cases New Technology was moved to design implementation without the CPs or CSs clearly defined. It was also indicated that new technology capability is substantially reduced when it is considered from the implementation perspective.

Assessment

1. **Assessments should consider individual feature variation and the impact of feature variation on system requirements using KC flowdowns.** *(Good)*

   CPI and CPD processes require the impact of all CPs and CSs be evaluated from feature level up to the product level.

2. **Assessment activities must be shared and coordinated among organizational functions and CFTs.** *(Good)*

   Program Teams, CFTs, QFD flowdowns, Critical Parameter Tracking forms and SEDIR databases help to facilitate this requirement.

3. **Information/documentation from assessment activities must be maintained and accessible.** *(Good)*

   Use of FAST Diagrams, IOC Flowdowns, SEDIR, QFD Flowdowns, CP Tracking Lists, Critical Parameter Growth Curves and CP Databases are standard forms used to capture assessment information.

4. **Assessment must be used to validate potential KCs before they are considered for mitigation.** *(Good)*

   CPD and CPI processes have clearly defined steps that evaluate all potential CPs/CSs to ensure they are valid before mitigation is considered.

5. **Assessments of robustness should be based on quantitative measures through use of hardware, analytic models and/or computational systems.** *(Moderate)*

   CPD and CPI require use of models and/or experimental hardware to assess CPs and CSs. Interviews have indicated that use of hardware and models does, however, vary across developments.

6. **Assessment should measure the impact of dimensional variation on functional performance.** *(Good)*

   Relationships between CPs and CSs ensure that the impact of dimensional variation to functional variation is considered.

7. **Assessment should use process capability feedback information for the analysis whenever possible.** *(Moderate)*

   Process capability assessments are performed as a required step in CPD and CPI. Process capability data is obtained from databases or analysis of current production systems. According to interviews the extent to which process capability is maintained for existing processes and used for new products varies across developments. Process capability data may be somewhat problematic since it is usually just a snapshot in time and may not represent real variation over time.

8. **Assessment should prioritize validated KCs to ensure proper application of mitigation alternatives.** *(Moderate)*

   CP Tracking Forms and QFD flowdowns both require prioritized information to be determined and recorded to help structure resource allocation. The Quality Reliability Sensitive Parts Process is used to prioritize manufacturing and tooling efforts that involve CPs and CSs and place added attention on process quantification for these items. Interviews have indicated that CPs or CSs are not consistently prioritized for every development.

Mitigation

1. **Mitigation activities must consider the impact of the mitigation alternatives on the overall product.** *(Good)*

   Use of Program Teams, Integrated System Design and CPM procedures ensure consideration of mitigation alternatives to the overall product.

2. **Mitigation must be a collaborative decision between multiple organizational functions (internal and external).** *(Good)*

   Program Teams, Integrated System Design, Product and Process Design Reviews and Continuous Supplier Involvement help to support collaborative decisions between multiple organizational functions. Interviews have revealed that interactions between external functions are not consistent.

3. **Mitigation activities and decisions should be documented.** *(Good)*

   Critical Parameter Management Plans, Production and Quality Control Planning Matrix, SEDIR, QFD Flowdowns, CP Tracking Lists, Critical Parameter Growth Curves, and CP Databases record mitigation information.

4. **Mitigation activities must be prioritized according to the risk of KCs.** *(Moderate)*

   Interviews have reflected that mitigation alternatives are not always prioritized based on the risk of failures.

5. **Mitigation should select alternatives that support robust designs helping to minimize the total number of KCs needing to be controlled in production.** *(Good)* h

   Robust Design methods are an integral part of CPM activities. CPM requires Experimental Hardware or Models to be developed and nominal values and latitudes (tolerance ranges) for CPs or CSs to be based on optimization techniques. Also, Design for Manufacturing (DFM) and Design for Assembly (DFA) are both used to review the design ensuring the product is robust.

6. **The selection of a mitigation strategy should be based on the cost and cost benefit data.** *(Moderate)*

   Interviews have indicated Xerox has numerous difficulties making cost tradeoffs between mitigation alternatives. It appears that the lack of accurate cost data or cost models are common problems preventing consistent cost-based tradeoffs. However, in situations where cost data does exist, it is generally used to make tradeoffs.

Communication and Documentation

1. **Documentation and Communication must support the exchange of information throughout and between developments, between organizations and throughout VRM stages (identification, assessment, and mitigation).** *(Moderate)*

   Product Archives, FAST Diagrams, CP Databases, QFD Flowdowns, IOC Charts, SEDIR and CP Tracking Lists all help to support this requirement. Interviews have suggested that the level of documentation and communication is sometimes slow due to late capture and exchange of information by specific organizational functions or teams. It was also indicated the level of information exchange between individual developments is inconsistent. CPD and CPI sequence of activities requires information to be transferred from identification, to assessment and then to mitigation.

2. **Documentation and Communication must support flowdown and traceability of KC information.** *(Good)*

KC flowdown and traceability is achieved through use of FAST diagrams, IOC flowdowns and SEDIR, QFD Flowdowns, CP Tracking Lists, Outline drawings, and CP Databases.

3. **Documentation and Communication must support process capability feedback for identification, assessment and mitigation functions.** *(Good)*

   Based on CPD and CPI, process capability information must be obtained for VRM activities. A number of procedures outlined in TTM also require process capability feedback to be maintained. These TTM/VRM activities include Manufacturing Assembly Process Verification and Certification, Assembly and Test Process Capability Studies, Process Capability Reviews, Manufacturing Robustness and Readiness Assessment.

4. **Documentation and Communication must capture information necessary for reuse/legacy data.** *(Good)*

   Product Archive databases captures reuse/legacy data, which includes CP and CS information. Guidelines have been established to outline the expected amount of existing design information and technology that should be reused for all new product developments. Design rationale is usually missing from this type of documentation. This creates problems with reuse.

5. **Documentation and Communication must provide information necessary for measurement and inspection plans.** *(Good)*

   CP Tracking Lists, Critical Parameter Management Plans, Production and Quality Control Planning Matrix, and Product-Production Qualification/Test Plans all help to provide information necessary for measurement and inspection plans. The Quality Reliability Sensitive Parts Process is also used to place prioritization on critical path items (schedule related) that involve CPs or CSs.

Documented Instructions

1. **Documented instructions must have clearly defined goals and objectives for VRM.** *(Good)*

   Documented instructions for CPM, TTM and Engineering Excellence Fundamentals all have clearly defined goals and objectives for VRM activities.

2. **Documented instructions must provide sufficient training and supporting process materials.** *(Good)*

   Use of documented instructions, training guidelines, CPM/QFD Consultants and Portfolio Skills Assessments ensure sufficient training and supporting materials for individuals and teams.

3. **Documented instructions must ensure a consistent set of definitions and/or classifications is established and used.** *(Moderate)*

   Interviews have indicated the current classification scheme is not sufficient when distinguishing between parameters important to design and parameters that need to be controlled during production. It was also indicated CPs and CSs are not always distinguished from one another.

4. **Documented instructions should communicate the activities required when a KC is identified. This ensures that all organizational functions are aware of the consequences and/or reactive measures that result from a KC classification.** *(Good)*

   CPD and CPI outline required reactions and implications that must surround identified CPs and CSs. CPM requires that all potential CPs/CSs must go through CPD and CPD, which includes clearly defined assessment and mitigation requirements.

5.4 Assessment Summary

Assessment of Xerox's VRM process has revealed a number of supporting and unsupported activities and requirements that must be consider during the VRM Guideline development. The following discussion summarizes the findings.

5.4.1 Supporting Activities and Requirements

Xerox's Variation Risk Management is a continuous process that includes identification, assessment and mitigation functions. The VRM process continually evaluates the product throughout the development providing management of all CPs and CSs. The sequential process structure aligns assessment and mitigation of all identified CPs through careful CS selection and monitoring. Separate use of CP and CS ensure both functional and dimensional parameters are included in variation evaluation.

The entire VRM process is supported with well-established documentation and flowdown practices; this ensures supporting information is communicated throughout the development. Documentation, flowdown and communication are supported by defined standards for both paper and electronic information forms. VRM process requirements also enforce that information is made available to the proper organizational functions or CFTs. Extensive documentation and supporting resources ensure that VRM goals and objectives are clearly understood and training is made available to all individuals and teams as necessary for proper process execution.

The VRM functions are supported with a sound process that makes use of both quantitative and qualitative information. Assessments are commonly based on experimental/actual hardware or analytical models. Use of this hardware and models allows the nominal values and tolerance for CP and CS to be established. This is performed with optimization procedures such as parameter and tolerance design and validated based on quantitative analysis.

Robust and Integrated System Design methods are considered an integral part of the product development process. These methods require that the impact of variation be considered during

the development and overall system integration. This consideration helps to minimize the impact of variation at various product levels while optimizing the overall design.

5.4.2 Unsupported Activities and Requirements

Failure to complete outlined procedures is the most common problem associated with Xerox's VRM process. Most low assessment ratings can be connected to processes that were not performed to completion or to the extent defined by process requirements. Failure to complete the QFD process has a negative impact because it is used for flowdown for VRM information and to support communication between organizational functions. Proper execution of continuous supplier involvement appeared to reduce the effectiveness of communications with external suppliers and their compliance to CPM. Timely documentation and exchange of VRM information was also noted to impact execution of some assessment activities.

Problems directly associated to the VRM process are very limited. The largest problem appears to be prioritization of KCs. The apparent limited use of KC prioritization has impacted both assessment and mitigation functions. Because assessment resources are limited, prioritization proves beneficial by ensuring resources allocation based on expected KC risk. Limited availability of control resources in mitigation also requires a consistent KC prioritization scheme. In addition to prioritization, the classification of KCs was noted as being unclear or problematic in some situations. The most common problem involved confusion between parameters that were important to design as opposed to parameters that needed to be controlled in manufacturing.

6 Overview of the Identified Tools and Techniques

This chapter provides an overview of tools and techniques that are identified as *best practices* or *commonly used practices* based on the company assessments. The tools and techniques are presented in alphabetical order according to the defined VRM stages (i.e., identification, assessment and mitigation).

6.1 Identification

Identification tools and techniques support identification of potential KCs, definition of KC flowdowns and collection of supporting information for assessment and mitigation. Product development information must be reviewed by CFTs and organizational functions to identify high-risk areas of products and processes. These information sources can include customer requirements, government regulatory and safety requirements, company strategy and objectives, historical performance data, benchmarking data, rejection/scrap/rework records and other information of this type. Information reviews must be followed up by product-process requirement flowdowns. The product-process requirement flowdowns provide information to the product-level where KCs can be identified. Once potential KCs are identified, KC flowdowns are performed and supporting information is collected. All identified potential KCs must be passed on to assessment for validation prior to mitigation.

Cross Functional Teams

Cross Functional Teams are used extensively to perform and coordinate identification activities. Establishing CFTs is essential for integrating design and manufacturing to increase produceability of product designs [Susman1992]. CFTs are established to oversee design efforts for products and/or major product systems/subsystems. Companies with large-scale developments establish CFT structures (hierarchy of CFTs) to manage KCs throughout the product. In most situations, a product-level CFT oversees coordination for team structures. In best cases CFTs and CFT structures are established early in the development. Identification activities will start upon team formation and continue throughout all development phases. In situations where organizational functions do extensive design work, CFTs are provided a

preliminary list of KCs from these functions; this helps reduce the time required by CFTs to perform identification activities and ensure KCs are properly addressed for all product areas.

Quality Functional Deployment

QFD is a systematic process that helps identify customer and product-process requirements and deploy them throughout all activities of the development process [Clausing 1995]; this is often referred to as product-process requirement flowdown. This flowdown generally starts with Customer and Product requirements and continues through product levels to process control parameters. The most extensive use of QFD starts with a Preplanning Matrix and continues to a Production and Quality Control Planning Matrix. Preplanning Matrix can include Voice of the Customers, Parameter Prioritization, Competitive Benchmarking and Product Strategies. Production and Quality Control Matrix can include Manufacturing Process Specifications, Parameter Prioritization, Process Controls and Quality Controls. Between these two matrix, "Houses" will be developed for systems, modules, subsystems, components and manufacturing parameters. In most situations, QFD is used only to initiate identification activities. This approach includes one or two levels of flowdown taking product-level product requirements and deploying them to systems or subsystems. Beyond the first two levels, QFD flowdowns have been noted to become very large and unmanageable. When properly executed, QFD does provide good traceability of KC information.

Design and Process FMEA

Design and Process FMEAs are commonly used to help structure identification activities. FMEA techniques provide design and manufacturing teams a systematic means of studying cause and effect of product failures [Tatikonda and Tatikonda, 1994]. There are two common approaches to applying design FMEAs. The first approach considers products as a whole, which is generally a quick overview of all product levels. The second is to focus on specific product levels (i.e., systems, subsystems and components). The overall product approach is sufficient for small-scale designs, but can be unmanageable for large scale and/or complex designs. In situations where designs do not change FMEAs are often reused. Process FMEAs are often applied in conjunction with Design FMEAs and used to address manufacturing and assembly processes. Both design and process FMEAs provide a consistent structured means to evaluate

products and processes for potential KCs. They also provide a consistent format to record KC information. However, FMEAs do not provide sufficient traceability of KC information. There are no clear means of linking product level FMEAs (i.e. product, system, subsystem, components, etc.) making it difficult to observe interactions and relationships between KCs. Also, there are no effective means of linking Design FMEAs to Process FMEAs or FMEAs to control plans. Therefore it is important to realize that FMEAs must be used in conjunction with KC flowdown and traceability tools and techniques.

KC Classification

Use of KC classifications is often associated with identification activities. In many situations KC classifications will be determined based on information reviewed during identification. Classifications are used to distinguish KCs based on driving requirements, parameter type, criticality, responsibility and other information that can influence how KCs should be assessed and mitigated. Classification information can reflect prioritization, legal/safety, functional/dimensional, product/process, impacted systems and other information that influences KC management. Identifying symbols can be considered part of KC classifications. A range of symbols exists all with a common objective of highlighting KCs from other non-critical features. Alpha or numerical designators may also be included for tracking purposes.

KC Flowdown: Drawing, Schematic and Build Trees

The company assessments reveal several approaches intended to support KC flowdown. The most common approach is by using Drawing, Schematic and Build Trees (i.e., hierarchy between drawings based on physical interfaces and assembly sequences). In this approach, KCs are flown down through engineering and assembly drawings. Problems associated with this approach arise when KC relationships are not explicitly captured, thereby limiting traceability of KC information (i.e., source of variation, relationships between KCs, product-level impacts).

KC Flowdown: Functional System Analysis Technique

A second approach for KC flowdowns is performed based on a functional analysis of systems or subsystems. The flowdown is performed by mapping relationships between system functional parameters and dimensional specifications. These KC flowdowns provide sufficient information

to determine relationships between performance requirements and dimensional characteristics where variation can occur and must be controlled. The functional system analysis technique is not always applied to the overall product, but is commonly applied to individual systems or subsystems.

KC flowdown: Input/Output/Constraint Charts and Flowdowns

The third form of KC flowdowns technique maps relationships between major system/subsystem interfaces for the overall product. In this approach, inputs, outputs and constraints are defined for each major system/subsystem. Relationships and interactions between these systems/subsystems are then mapped and evaluated for negative interactions and potential sources of variation. This flowdown only reveals KC interactions and relationships at system and subsystem levels. This system interface flowdown is generally not sufficient to support a clear KC flowdown between source(s) of variation and overall product impact(s). Therefore it should be performed in conjunction with more explicit KC flowdowns.

KC Flowdown (Process): Process Flow Charts and Product/Process Interaction Techniques

KC flowdowns specific to production processes are used for process evaluations. These production process flowdowns utilize process flow charts and product/process interaction techniques to map relationships between product characteristics and process operations. Objectives are to identify specific operations where KCs are produced, altered, observed or can be controlled. These tools are used to support development of control plans based on identified relationships between product KCs and process operations. These flowdowns are not, however, specific to products and should not be considered a substitute for product KC flowdowns.

6.2 Assessment

Assessment tools and techniques help determine cost and probability of failure associated with identified potential KCs. These activities will utilize KC flowdowns and other supporting information provided from identification. Additional inputs must be collected from organizational functions and other design and manufacturing information sources. Assessment

results will determine if identified potential KCs are valid for mitigation activities. It will also prioritize KCs for mitigation based on associated risk.

Analytical and Computational Models

Analytical and computational models are used as substitutes for or in combination with experimental hardware to perform assessments. Use of these tools often depends on resource availability, design complexity and the accuracy to which models can be developed to support analysis. Robust Design, DOE, sensitivity analysis and statistical tools can also be used to test and optimize these models. Variability Simulation Analysis (VSA) is one model used to evaluate impacts of dimensional variation. Results from VSA provide quantitative assessments reflecting those features that have a high impact on form, fit and function. Finite Element Analysis (FEA) is another model used to determine the sensitivity of physical product features. Few modeling packages exist to assess the functional performance impacted by dimensional KCs.

Cause and Effect Diagrams, Root Cause Analysis and Fault Tree Analysis

Cause and Effect Diagrams, Root Cause Analysis and/or Fault Tree Analysis are all used to identify and define variation sources, potential failures and resulting impacts. These tools graphically illustrate relationships of causes and subcauses to an identified effect or problem. In many situations these techniques are used as reactive measures rather than proactive; they are often applied after designs are completed and problems arise in production.

Cross Functional Teams

As with identification, CFTs and CFT structures are vital to coordinating and executing assessment activities. Both CFTs and individual organizational functions can perform assessment This requires added coordination measures to ensure proper execution. On large-scale developments, when there are multiple teams for a single product, CFT structures are used to outline the responsibilities of each team. A product-level CFT will generally coordinate mitigation activities between multiple team structures.

Design and Process FMEA

Failure Modes Effects Analysis is often continued from identification to organize assessment activities. The assessment portion of FMEAs is used to specify potential effect(s), cause(s) severity, occurrence and failure modes. These are typically determined through CFT discussions. Most assessment results are only qualitative, because they are based primarily on team knowledge and experience. In some situations quantitative information will be used to support the assessments, but there is no means to distinguish qualitative from quantitative information. Risk Analysis worksheets, which are very similar to FMEAs, are also used to support assessments; results from these analysis are generally qualitative based.

Design for Manufacturing (DFM) and Design for Assembly (DFA)

Design for Manufacturing (DFM) and Design for Assembly (DFA) provides a systematic procedure for analyzing product designs based on proposed manufacturing and assembly processes to help reduce and eliminate potential problems [Boothroyd 1994]. These tools are simultaneous engineering processes used to optimize relationships between designs, manufacturability and ease of assembly. DFM and DFA guidelines define methods to evaluate and improve product produceability by reducing parts, operations and other opportunities that contribute to product variation. DFM and DFA do not, however, provide specific information for KC assessments. These tools should be used with assessment tool that do address KCs specifically (DOE, Analytical and Computational Models, FMEAs, Robust Design, etc.).

Experimental Hardware and Prototypes

Experimental hardware and prototypes are commonly used to test proposed designs for variation impact. Development and testing of this hardware is often performed in conjunction with such practices as Robust Design (parameter and tolerance design), Design of Experiments (DOE), sensitivity analysis and accelerated testing. These techniques provide a systematic approach to define inputs to testing apparatus in order to observe corresponding changes in outputs. Analysis is often performed through statistical analysis of observed outputs and predetermined inputs. Analysis of Variation (ANOVA) is commonly used for statistical analysis while conducting these experiments.

Process Capability Studies

Process capability studies are the most common source of quantitative information for assessments. These studies are used to determine if manufacturing and assembly processes will support product specifications. Studies are applied to new and existing manufacturing processes, assembly processes, measurement systems, gauging systems and other processes required to support production. Process capability studies can be based on models, hardware or actual process measurements.

Quality/Cost Loss Functions

Taguchi Quality Loss Functions help to correlate expected loss with variation of specific parameters or features. When loss functions of specific parameters are compared to process capability data, it is possible to determine expected loss due to expected variation. These functions will help determine when costs are significant and variation should be controlled. In most situations, these functions can be determined for product level parameters, but are not easily determined for detailed-part parameters.

Tolerancing Procedures and GD&T

Tolerance analysis and tolerancing procedures, including datuming/indexing and Geometric Dimensioning and Tolerancing (GD&T), are often integrated procedures of assessment activities. Tolerancing methods must be used to ensure that designs properly reflect design intent and performance requirements. In many situations, blanket tolerances or historical (i.e., used in the past) tolerances are applied without consideration of impact to overall product performance. Techniques including arithmetic tolerancing, worst case, statistical tolerancing, Root Sum Square (RSS) and Monte Carlo simulations can be used to evaluate the impact of allocated tolerances. Established datum procedures are used to ensure datums align with tool indexing and that datum transfers are minimized when KCs are involved. Focusing attention on datum selection and coordination is very effective for reducing variation due to misalignment between design, manufacturing and assembly activities.

6.3 Mitigation

Mitigation tools and techniques are used to select strategies to resolve or control validated KCs passed down from assessment. These activities will utilize KC flowdowns and supporting information provided from assessments. There are four possible mitigation alternatives that can be used separately or together: design changes, process changes, control measurement plans and variation reduction. All mitigation alternatives must be based on collaborative decisions between organizational functions and/or CFTs.

Control Plans and Communication Plans

Control plans and instructions outline requirements for all mitigation strategies selected for controlled KCs. Control plans can include activities necessary to inspect, monitor and react to product and process KCs. These plans and instructions can address a single process or complete series of manufacturing and assembly sequences. Control plans are applied to manufacturing, tooling, gauging and assembly related processes that can or will influence controlled KCs. Communication plans are often established to coordinate follow-up mitigation activities for KCs that have not been resolved or defined on control plans.

Cross Functional Teams

CFTs and CFT structures are vital for ensuring mitigation alternatives are based on collaborative decisions. CFTs are used extensively for evaluating assessment results and selecting effective mitigation strategies. CFT structures support mitigation based on a system perspective for large developments. Procedures such as Integrated System Design, Design Reviews, Process Acceptance Requirements, Production Part Approval Process and Feasibility Commitment Reviews are often established to ensure assessments have been properly completed and mitigation is coordinated from a system perspective.

Design and Process FMEA

Failure Modes Effects Analysis can be continued from assessment to help outline and prioritize mitigation alternatives. Completion of standard FMEA reports will generate recommended actions, responsible functions, target completion dates and corrective actions taken. These reports will also include severity, occurrence, detection and Risk Priority Number (RPN) ratings

that provide a qualitative prioritization for KCs. Design and Process FMEAs are often reviewed during control plan development. Because FMEAs are primarily quantitatively based, they should not be used as the sole basis for selecting mitigation strategies. FMEAs do not provide sufficient traceability between FMEAs, identified KCs or to the overall product. FMEAs should be used in mitigation practices that provide quantitative analysis and clear ties to control plans (Cost Models, Cost/Loss Functions, Operating Window Concept, Tolerance Design, Control Plans, etc.).

Operating Window Concepts and Cost/Loss Functions

Operating Window Concepts (see Figure 11) are used to illustrate relationships between groups of KCs. These windows are used to graphically display nominals and acceptable ranges between two or three parameters. Cost/Loss Functions also provide a similar graphical perspective of loss associated with variation. Use of these models can help determine tradeoffs between KCs, customer perceived losses and probabilities of failure. Results from this analysis provide alternative design tolerances based on defined acceptable operating ranges and expected losses.

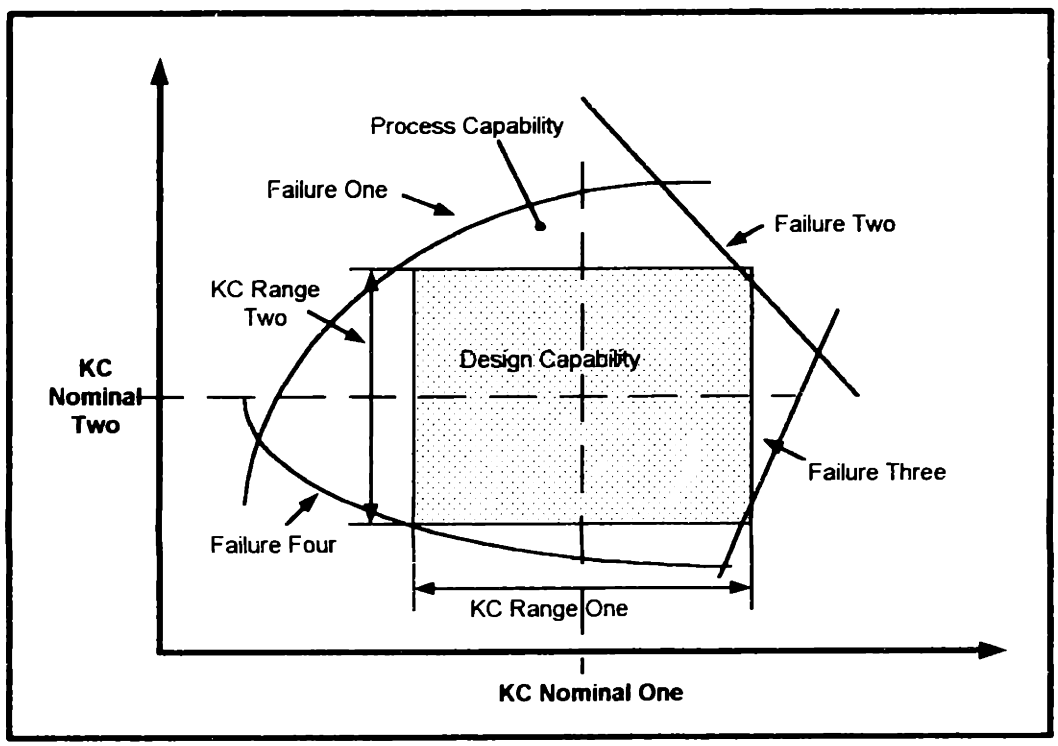

FIGURE 11: ILLUSTRATION OF THE OPERATING WINDOW CONCEPT

Statistical Process Control

The most common form of mitigation strategy is Statistical Process Control (SPC). SPC is used extensively in production environments to confirm that processes are capable and in control. A number of control charts exist to interpret and communicate process capability information. These charts provide quick feedback on the current state of processes associated with KCs. The effectiveness of SPC is highly dependant on targeting product and process parameters that have high impact on KCs. Effective SPC also requires corrective actions to be defined for situations when processes go out of control. Selection of SPC measures and corrective actions plans are generally performed through CFTs assigned to develop the process control plans.

Tolerance Design

Tolerance design is used in some situations to optimize systems through careful selection of settings for identified control and noise factors. By determining the signal to noise ratios and the slopes for these factors, systems can be optimized, thus minimizing the impact of parameter variation. These techniques can be applied to experimental hardware and analytical or computation models.

6.4 Documentation and Communication

Documentation and communication are used to support exchange of information between VRM stages, organizational functions, product development phases and product developments. Documentation and communication ensure KCs are understood and managed in an efficient manner. Capture of this information will also support traceability and reuse of KC information.

Databases

Electronic databases are used to support documentation and communication of KCs and VRM information. These databases help manage FMEA reports, CP tracking forms, IOC charts and product requirements. Product Archive databases are also used to record KC and product design information for reuses purposes. Other electronic forms of KC information include surrogates that define datums, locator, and measurement points that can be reused for VSA and CAD/CAE tools.

Identification, Assessment and Mitigation Tools and Technique Reports

Most of the tools and techniques discussed in previous sections directly support documentation and communication for VRM. QFD, FMEA, KC Flowdowns, Root Cause Analysis all generate KC documentation. Other mentioned tools and techniques indirectly generate KC information such as SPC, capability assessments, drawing and build trees, product and process design reviews/validation, DFM/DFA and VSA. Results or reports from these discussed tools and techniques are often the primary means for capturing information specific to KCs. Product design documentation is also relied on to manage KC information, but this does provide clear traceability of VRM information.

KC Tracking Forms and KC Management Plans

KC tracking forms and KC management plans are two forms of documentation that are specific to KCs. Tracking forms are used to monitor KCs from identification through assessment and into mitigation. These forms record supporting information which can include tracking numbers, parameter descriptions, units, classifications, parameter specifications, process capability, designer comments, potential failures and recommended controls. KC management plans focus specifically on activities defined to mange all identified KCs; these plans are transferred to organizational functions and CFTs to outline specific mitigation strategies.

6.5 Documented Instructions

Documented instructions are used to outline activities and requirements for VRM execution. These instructions should clearly define VRM goals and objectives, KC definitions and classifications, training procedures and process instructions. These documents can be specialized or standardized depending on the company's need.

Standardized and Specialized Manuals

Several forms of documented instructions exist to support VRM. Companies using several different suppliers generally developed standardize instructions. The AAIG manuals (FMEA, QS-9000, PPAP, SPC, FMEA, MSA) are provided by automotive companies to outline

requirements and procedures that include VRM application. HVC and AQS are similar to AAIG manuals that are used by aircraft companies. In addition to these standardized manuals, there are several specialized forms of documented instructions. In addition to documented instructions, consultants, coaches and Application Engineers (AE) are generally used to support proper execution of VRM procedures. Portfolio skill assessments are commonly used to help determine training required by individuals and CFTs for specific applications.

6.6 Summary for Tools and Techniques

A range of VRM supporting practices (i.e. tools, techniques, documentation, communication and documented instructions) are presented in this chapter. Each of these practices can serve a specific or range of functions to the overall VRM process. Most processes have both advantages and disadvantages associated with their use. It is also very clear that no single practice is capable of support VRM in its entirety. As a result, a set of these supporting practices must be selected based on the specific application of the VRM process. In many situations this set of implemented practices will also vary across companies and may vary between developments. Because there are numerous arrangements of these supporting practices it is only possible to suggest practices that will support all VRM procedures. The supporting practice selection must be performed based on a company's specific needs for VRM. It is recommended that each company first determine their intended use for VRM and dominated KCs and then select a set of supporting practices. Once a preliminary set is selected, they must be reviewed to ensure the overall VRM process is supported and there is clear alignment between these practices. In the following chapter the VRM guideline outlines all required procedures for VRM. Supporting practices are listed for each procedure. Companies can review this list to help select a set that aligns with their VRM application and overall company needs.

7 Variation Risk Management Guideline

This chapter introduces the proposed Variation Risk Management (VRM) Guideline. The guideline is presented through process flowcharts and detailed discussion. Supporting tools, techniques, documentation and communication practices are outlined on the flowcharts and in detailed discussion. The chapter concludes with overview comments on the VRM guideline.

7.1 VRM Guideline

The VRM guideline is a defined sequence of procedures that outlines the execution of complete execution of VRM. As discussed in Chapter 1, VRM involves *identification*, *assessment* and *mitigation* of risk driven by variation sensitive product and process parameters. Figure 12 illustrates a general VRM process flow and the interactions between the three primary stages. Figures 13-15 expands this basic process flow by defining specifically required procedures for each VRM stage. Each procedure has a corresponding list of supporting practices described in Chapter 6. These have been linked to each VRM procedure on the flowchart in Figures 13-15.

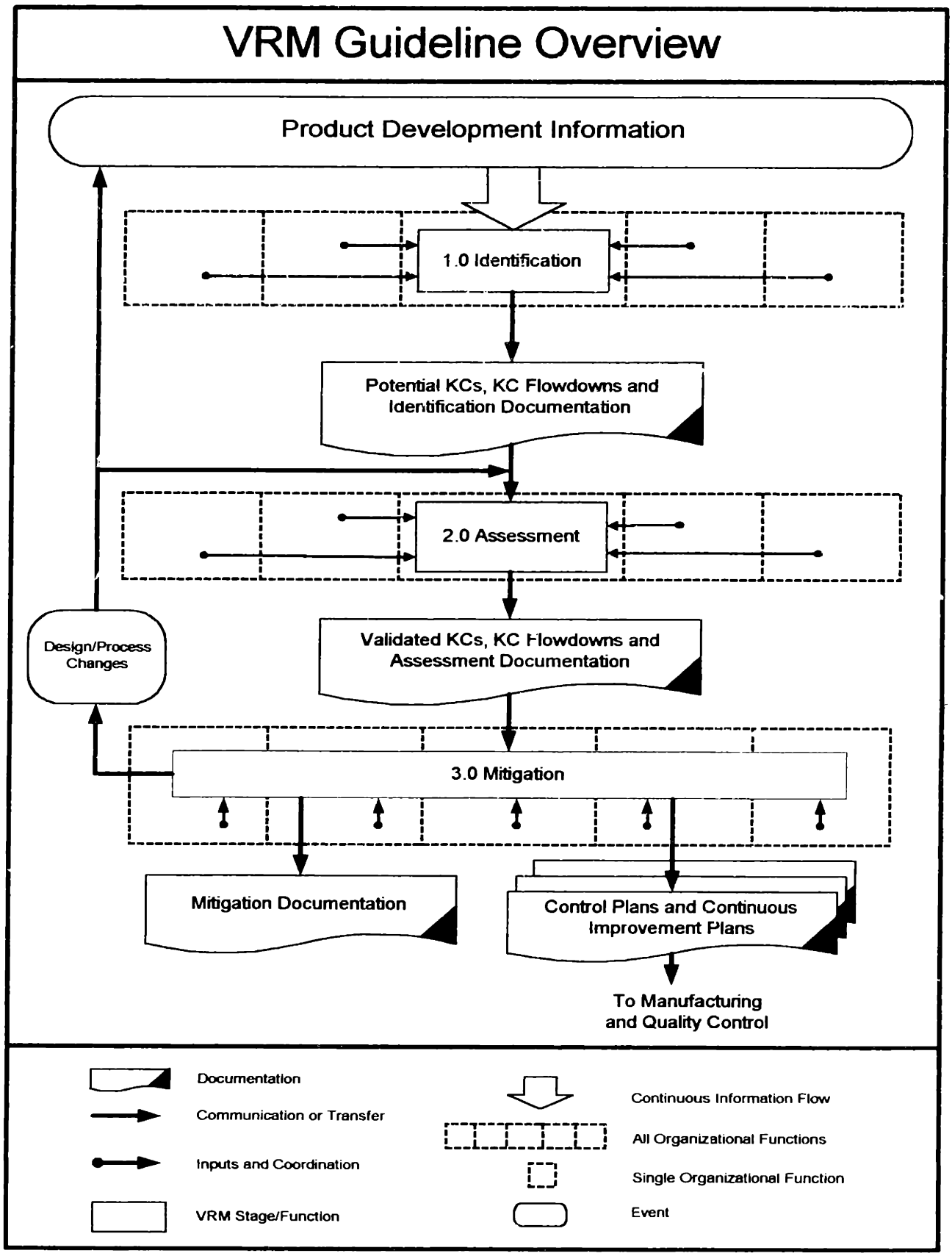

FIGURE 12: VRM PROCESS OVERVIEW

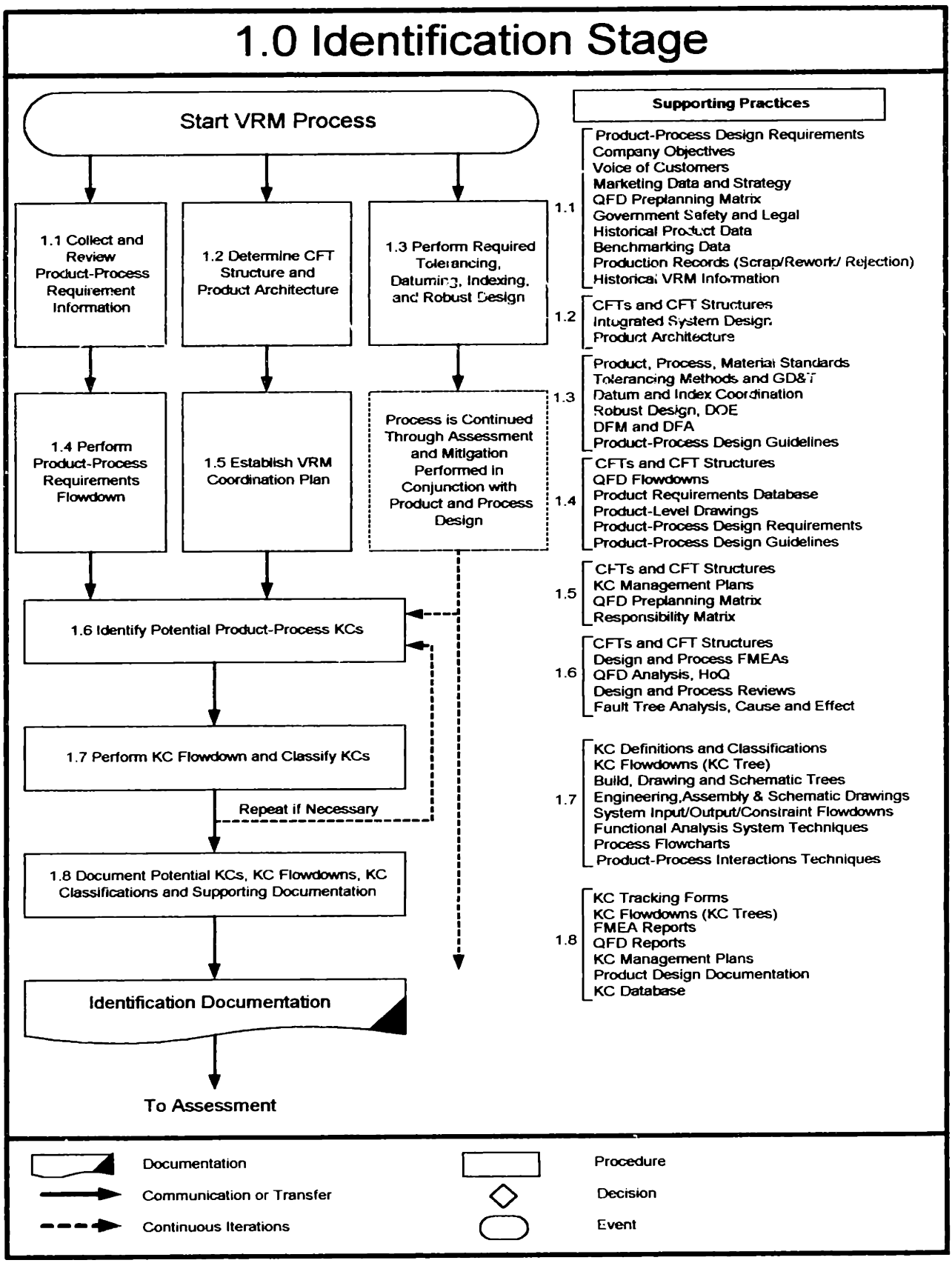

FIGURE 13: IDENTIFICATION STAGE PROCEDURES AND SEQUENCE

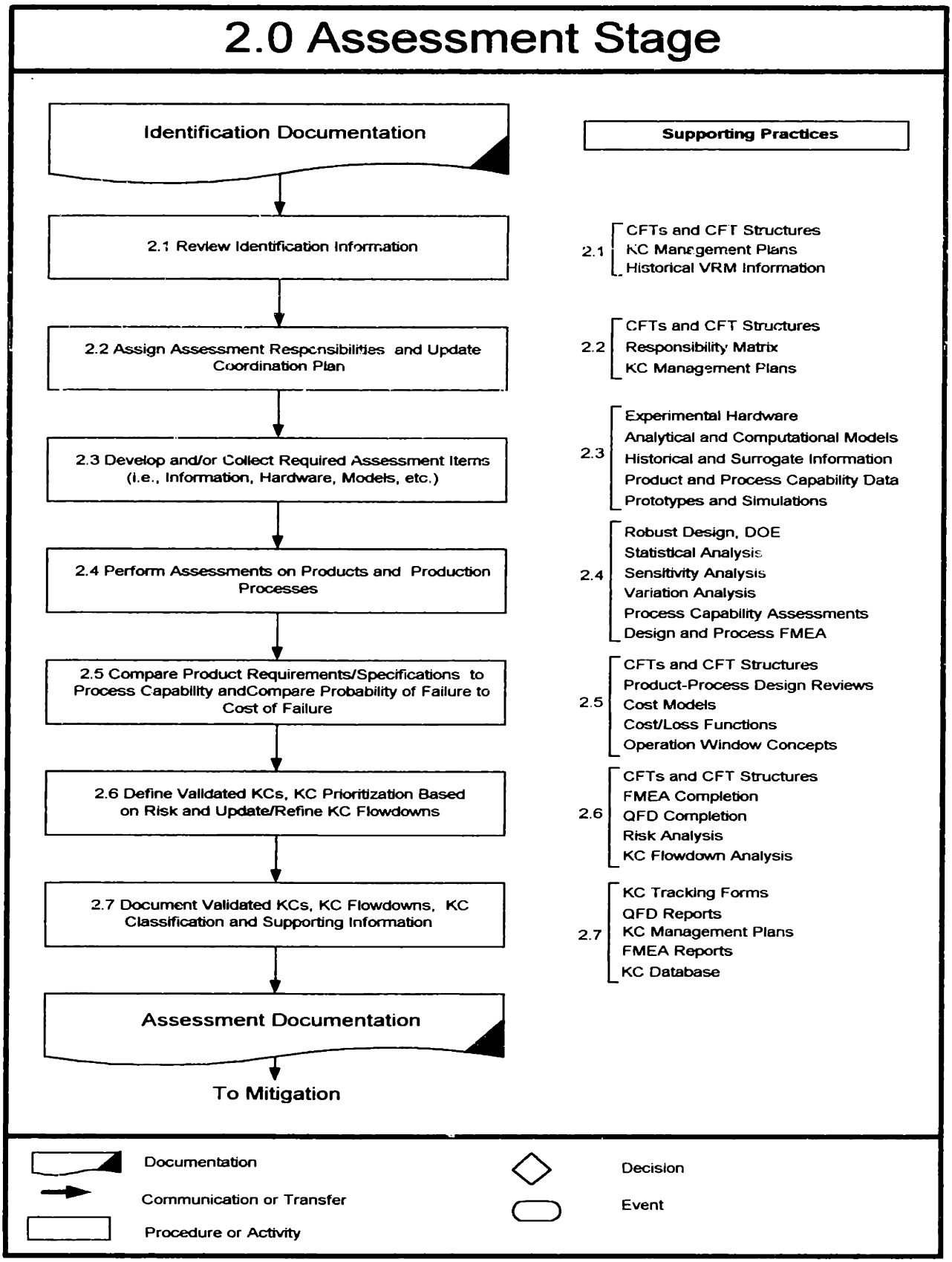

FIGURE 14: ASSESSMENT STAGE PROCEDURES AND SEQUENCE

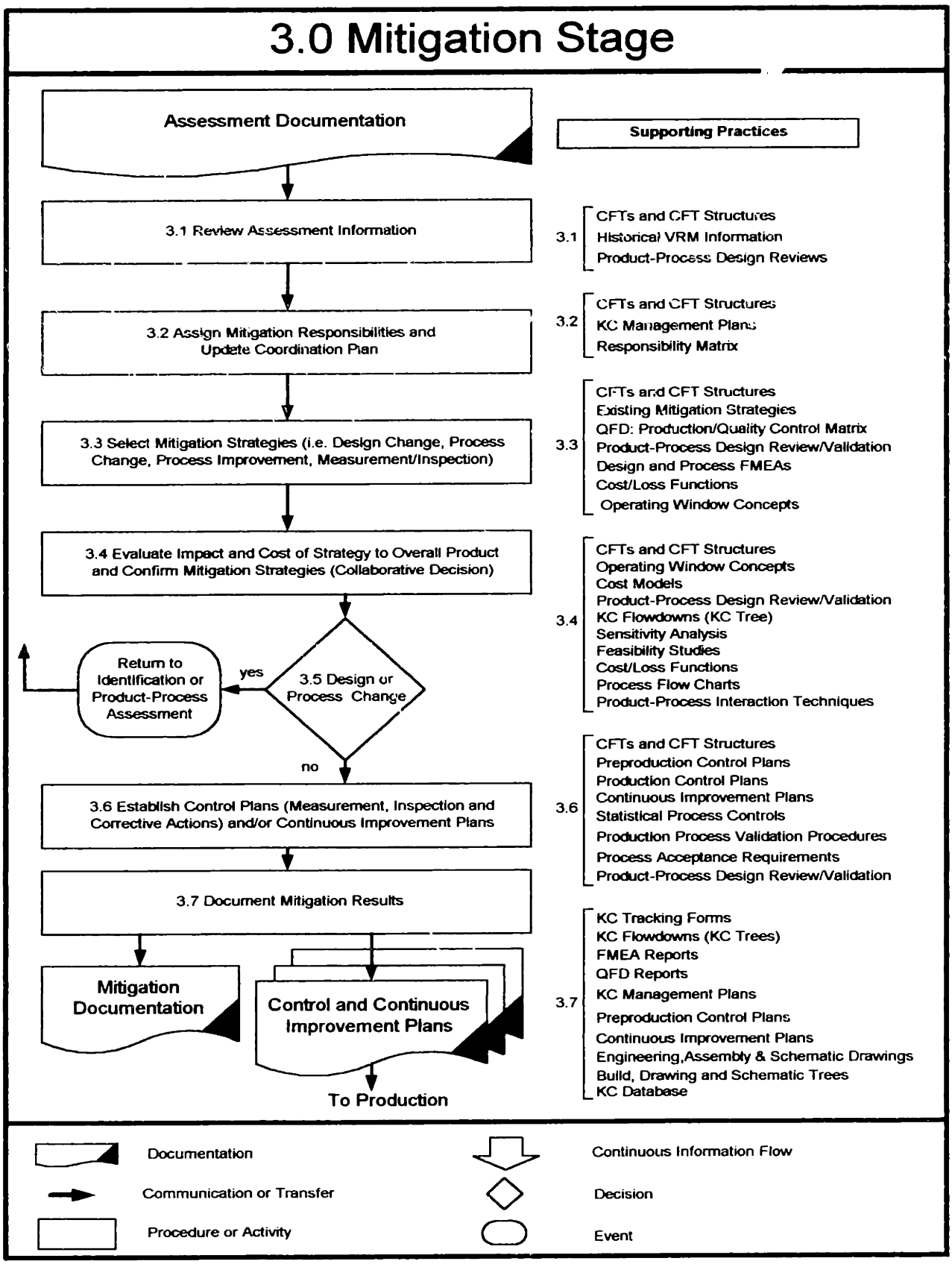

FIGURE 15: MITIGATION STAGE PROCEDURES AND SEQUENCE

7.2 Procedure Descriptions and Recommended Practices

The following discussion provides additional explanation for each guideline procedure. This discussion also briefly discusses tools, techniques, documentation and communication practices that have been identified to support these procedures.

7.2.1 Identification Stage Procedures

Figure 13 illustrates the sequence of procedures required for identification.

1.1 Collect and review product-process requirement information: Identification involves continuous review of the product development information (i.e., all information associated with current and previous developments). Development information can include customer requirements, government regulatory and safety requirements, company strategy and objectives, historical performance data, benchmarking data, and rejection/scrap/rework documents, historical VRM and other product documentation. Review of development information leads to identification of product-process requirements information, used to identify high-risk product or process key characteristics. The product-process requirement information must be flowdown to lower-level teams or product levels where potential KCs are identified. Identified potential product-process KCs will initiate the KC flowup/down that is performed in procedure 1.7. Figure 16 illustrates the information exchange between product development information, product-process requirements flowdowns, product-levels, production processes, potential product-process KCs and KC flowup/downs. This figure indicates that requirements will be flown down to product-levels or production operations where the requirements may influence potential KCs. At this level or operation an analysis is performed identify potential product-process KCs. Identified potential KC will lead to an explicit KC flowup/down (procedure 1.7) that identifies product-level impacts, sources of variation and relationships/interactions between KCs. Multiple potential KCs and Flowdowns can be performed for a product or the production processes. The reverse of this flow ensures feedback is provided to ongoing product development activities.

Supporting practices: Product-level CFTs are responsible for collecting and reviewing this information, most of which is defined and captured during product design activities. A QFD

(Preplanning Matrix) helps record and organize all applicable product-process requirement information. Historical VRM information should reveal existing problems related to KCs.

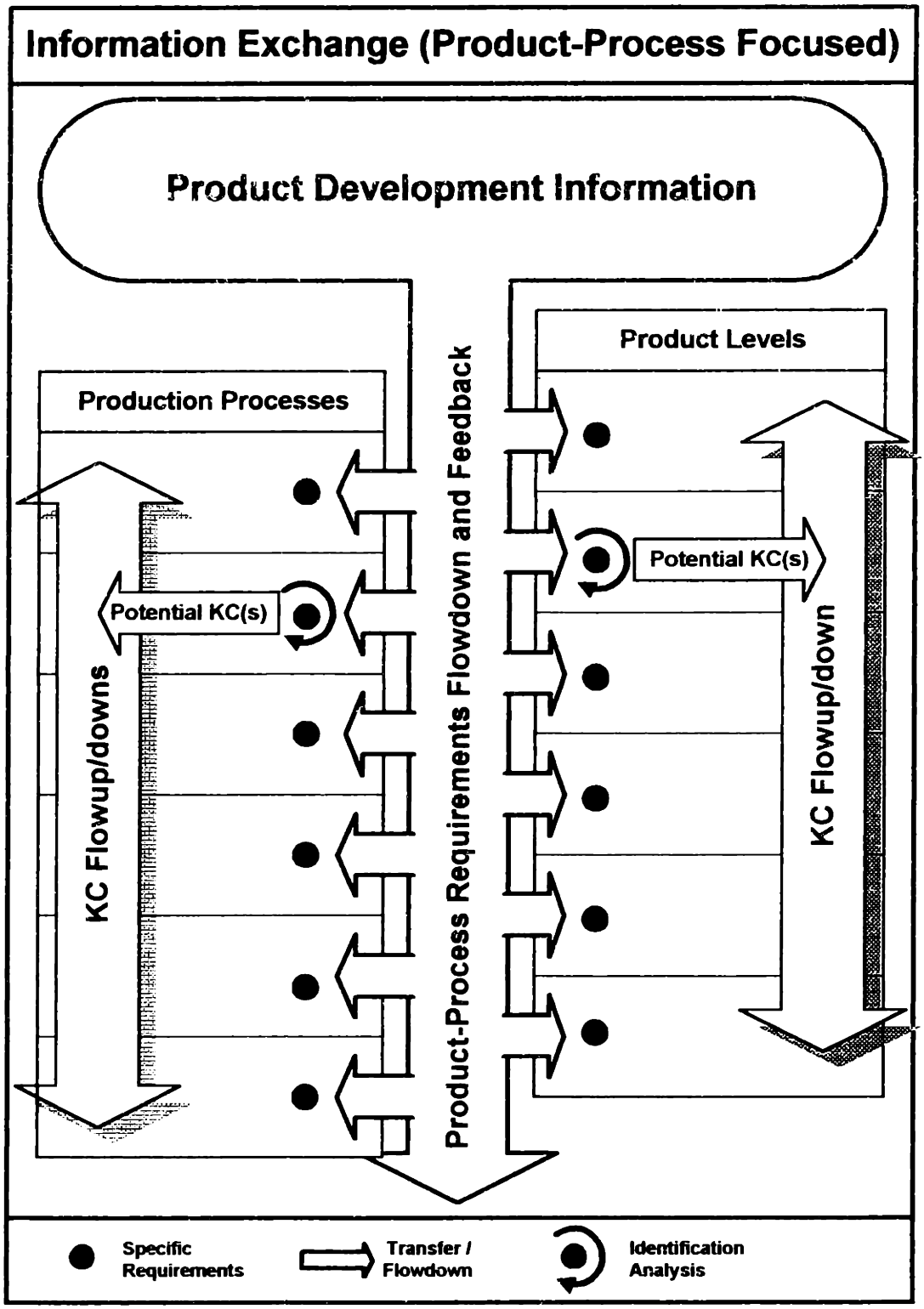

FIGURE 16: ILLUSTRATION OF INFORMATION EXCHANGE THAT IS PRODUCT-PROCESS FOCUSED

1.2 Determine CFT structure and product architecture: This procedure ensures CFTs and CFT structures are established and aligned with the product architecture. The defined team structure must support interactions between CFTs managing separate areas of the product (i.e., systems, modules, subsystem, components, etc.). On large-scale developments, a product-level team may be established to oversee all lower-level teams. A representative may be selected from lower-level teams to participate on the product-level team as illustrated in Figure 17.

Supporting practices: This procedure is accomplished by first establishing a product-level CFT and then using this team to define the product architecture. The product-level CFT then establishes a CFT structure to align with this product architecture. On small-scale developments a CFT structure may not be required, but the product architecture will influence management and flowdown of KCs. The product architecture defines interfaces and interactions between product levels (i.e., systems, subsystems, modules, components, etc.).

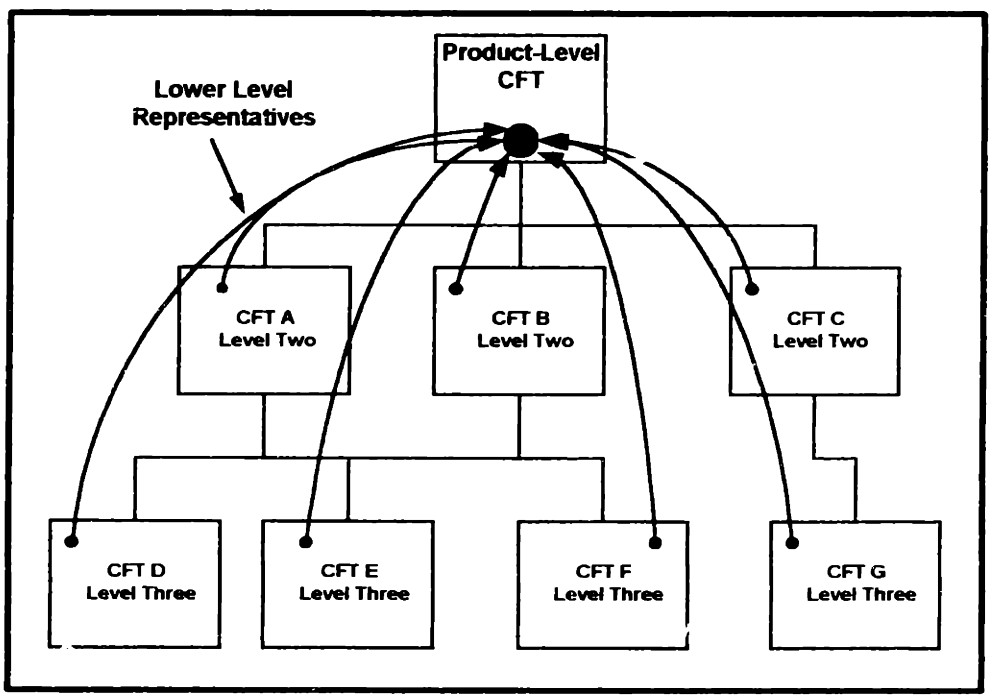

FIGURE 17: ILLUSTRATION OF CFT STRUCTURE AND REPRESENTATIVE INVOLVEMENT

1.3 Perform required tolerancing, datuming, indexing and robust design: VRM and design for robustness activities must be concurrently executed. This can be accomplished through four practices: tolerancing, datuming, indexing and robust design. These supporting practices should

be continually applied throughout product development as problems are identified and assessed as problematic. This ensures tolerances reflect design intent, datums are aligned with tooling indexes and robust design practices are applied.

Supporting practices: GD&T, Statistical Tolerancing, Tolerance Analysis, Datum and Index Coordination, Robust Design (Parameter and Tolerance Design), and Design of Experiments (DOE) directly supporting procedure 1.3. Additional product and process optimization practices include Design for Manufacturing (DFM) and Design for Assembly (DFA); however, these practices do not consider the impact of KCs directly. Product, Process, and Material Standards and Product-Process Design Guidelines provide predetermined instruction and criteria for application the listed practices.

1.4 Perform product-process requirements flowdown: After product-process requirements have been collected and reviewed (Procedure 1.1) product-level CFTs will flow the system requirements down to lower-level CFTs and/or product levels to support KC identification.

Supporting practices: Product-level CFTs initiate the flowdown procedure, which should align with the CFT structure and product architecture. QFD (HoQ) provides a structured method for performing and documenting the product-process requirement flowdown; in many cases this requirement flowdown will be reduced to manage only KC information. This reduction is important. It eliminates product requirements that are not related to KCs, keeping the QFD flowdowns manageable. Product Requirements Database and Design Requirements and Objectives support documentation and communication in product-process requirement information. Product-level Drawings document product-process requirements that apply to physical features or major interfaces of the overall product.

1.5 Establish VRM coordination plan: Coordination plans link together the Product-level CFT, CFT structure (when applicable) and product architecture within the VRM activities. Coordination plans define VRM responsibilities and coordinate identification and continuation of VRM activities; this plan must be updated for assessment and mitigation activities. A coordination plan should capture the product architecture and CFTs or organizational functions responsible for each section of the product. This plan should also outline the ordering in which sections are developed and how this timeline imposes requirements on later developing sections.

Figure 18 illustrates the information exchange between product development information, product-process requirement flowdowns, CFTs, CFT structures, organizational functions and coordination plans/responsibility matrix. This figure indicates that requirements will be flown down through the CFT structure and organization functions to areas the requirement will impact. At these CFT levels or organizational functions, analysis are performed to determine how the requirements impact their specific area and identify any potential KCs that must be feedback to the CFTs. The Product-level CFT is required to review the product-process requirements, specifically the product architecture, compare it to the CFT structure and/or involved organizational functions and define the coordination plan and assign responsibilities. All identified potential KC must transfer to the CFTs for final identification and to perform the KC flowdown. The reverse of this flow ensures feedback is provided to ongoing product development activities.

Supporting practices: Product-level CFTs define the coordination plan based on product architecture and CFT structures identified in procedure 1.2. The QFD (Preplanning Matrix) documents the product architecture and records team responsibilities for continued QFD application and/or VRM activities. A Responsibility Matrix outlines assigned responsibilities for VRM as well as design activities. KC Management plans can also be established to capture and outline all coordination activities specific to VRM.

1.6 Identify potential product-process KCs: This procedure identifies potential product KCs. Product-Process KCs should be motivated by or linked to product-process requirements identified during procedures 1.1 and 1.4. Product KCs will initiate the KC flowdown in procedure 1.7.

Supporting practices: CFTs support identification of product KCs, which are often performed during design and process reviews. Design and Process FMEAs structure identification activities and record VRM information. Continued execution of QFD (HoQ) will also lead to the identification of product KCs and establish a format that can lead into a KC flowdown. Fault Tree Analysis, Root Cause Analysis and Cause and Effect Diagrams help identify product KCs and their potential impacts to the product.

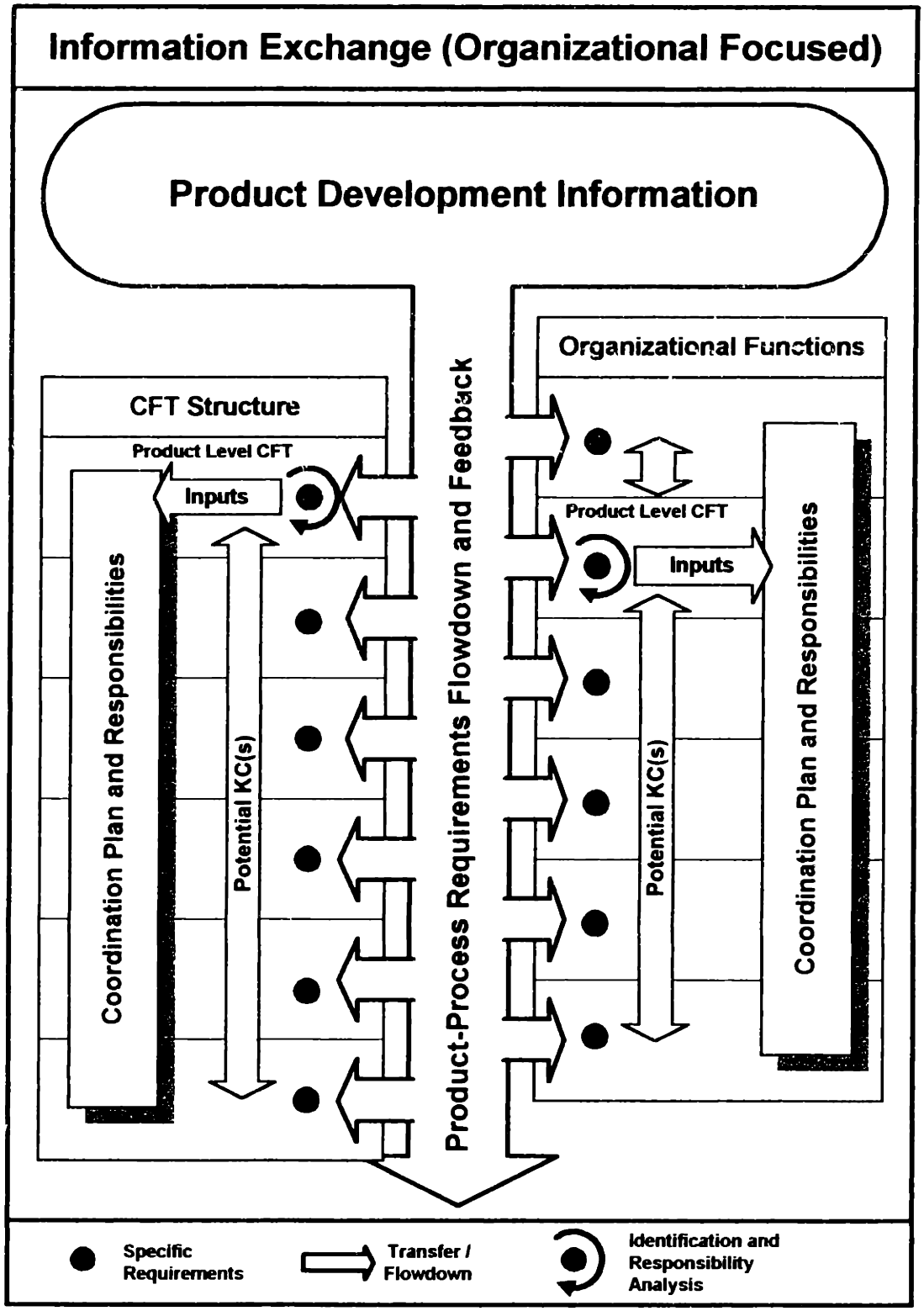

FIGURE 18: ILLUSTRATION OF INFORMATION EXCHANGE THAT IS ORGANIZATIONAL FOCUSED

1.7 Perform KC flowdown and classify KCs: KC Flowdowns capture hierarchical relationships/interactions between product KCs, source(s) of variation and overall product

impact(s). KC classification captures the KC importance (i.e., safety, legal, cost, produceability, design importance, origination, responsible group, validation, etc.) to help guide assessment and mitigation activities.

Supporting practices: The KC flowdown defines hierarchical relationships between product requirements, product KCs, and detail/feature level KCs resulting in a KC Tree. Functional System Analysis Techniques perform KC flowdowns by evaluating specifications that impact overall system functions. Engineering, assembly and schematic drawings indirectly support KC flowdowns based on the ordering of these drawings; this ordering is generally outlined in build, drawing and schematic trees. QFD support KC flowdowns when continued from procedure 1.4. System Input/Output/Constraint Charts and Flowdowns provide KC flow down between system and subsystem interfaces. Process Flow Charts and Product/Process Interaction Techniques help tie the KC flowdown to production processes. KC definitions and classifications should be outlined in process instructions and defined based on the company's needs; common classifications include legal/safety requirements, critical product parameters, critical product specifications, and critical process parameters.

1.8 Document potential KCs, KC flowdowns, KC classifications and supporting documentation: All identified KCs, KC flowdowns, classifications and additional information must be documented. The flowdowns and classification support traceability and reuse. Identification information will be required to perform assessment activities.

Supporting practices: KC Tracking Forms, KC Management Plans, KC Flowdowns, FMEA Reports, QFD Reports, Product Design Documentation and KC Databases all support this VRM documentation procedure. Whatever method(s) is selected, it should be aligned throughout all three VRM stages.

7.2.2 Assessment Stage Procedures

Figure 14 illustrates the sequence of procedures that is performed during assessment.

2.1 Review identification information: The identification stages generated a set of potential KCs, KC classifications and KC flowdowns. The combination of this information should reflect what measures and resources are required to assess the KC and impacted systems.
Supporting practices: CFTs are almost always used to perform this procedure. KC management plans often include identification information and outline follow-up assessment requirements (i.e. models, analysis, group discussions, process capability data, etc.). Historical VRM information (i.e., existing assessment resources, previous assessments on similar KCs, existing process capability data, etc.) should also be reviewed for previous assessment resources and practices that can be reused.

2.2 Assign assessment responsibilities and update coordination plan: This procedure assigns assessment responsibilities and updates the VRM coordination plan. Qualified CFTs or organizational functions are assigned assessment responsibilities based on their qualifications or specialization. The coordination plan should be updated to reflect assessment activities between lower-level CFTs based on product architectures.
Supporting practices: Product-level CFTs are responsible for updating the coordination plan based on expected interactions throughout the CFT structure and product architecture. Responsibility Matrix and KC Management Plans record and communicate responsibilities and coordination activities.

2.3 Develop and/or collect required assessment items (i.e., information, hardware, models, etc.): Most assessments require special hardware, models, capability information, CFT inputs and other supporting resources. Historical VRM information should be considered a source for information and a guide to resources that may be reused.
Supporting practices: Experimental hardware, Analytical and Computational Models, historical and surrogate information, Product and Process Capability data, Prototypes and Simulations are all items that may need to be developed or collected to support this procedure. Required items must be determined based on specific KCs.

2.4 Perform assessments on products and/or production processes: Assessments determine the probability of failure and cost of failure for identified potential KCs. Probability of failure will

be determined from process capability assessments. Cost of failure will be based on product design assessments. Assessments should be based on quantitative data, but both qualitative and quantitative assessments must be supported. Results from these assessments are absolutely essential for proper execution of all remaining activities. The results will be used to validate KCs and to justify mitigation strategies.

Supporting practices: Robust Design (parameter design), Design of Experiments (DOE), Statistical Analysis, Sensitivity Analysis, Variation Analysis and Process Capability Assessments are all practices that provide quantitative assessment information. Design and Process FMEAs help structure this activity; however, FMEAs provide only qualitative information.

2.5 Compare product requirements/specifications to process capability and compare probability of failure to cost of failure: This procedure determines if the process capability meets the product requirements and/or specifications related to KCs. For all KCs that the capability is not sufficient, the risk must be determined by comparing probability of KC failures to cost of KC failures. This risk will be used to influence prioritization of KCs for mitigation; this risk will also be used in procedure 2.6 to reflect which KCs are valid for mitigation.

Supporting practices: CFTs perform these comparisons and are often scheduled through design and process reviews. Operating Window Concepts, Taguchi Cost/Loss Functions and Cost Models are three tools that can help perform and/or visualize assessment information used for these comparisons.

2.6 Define validated KCs, KC prioritization based on risk, and update/refine KC flowdowns: During this procedure valid KCs are identified (i.e., Low-Probability/Low-Cost are not passed on to the mitigation stage). Validated KCs must be prioritized to ensure mitigation strategies are influenced by expected risk; the mitigation strategy should be based on risk of KCs and cost of control. This procedure will be used to update and refine KC flowdowns reflecting results from assessments; updated KC flowdown information can include percent contribution and expected interactions and/or relationships between identified KCs.

Supporting practices: This procedure is commonly performed by CFTs. FMEAs, Risk Analysis and QFD help structure this procedure and capture the required information. KC Flowdown review determines the interactions between KCs and variation impacts to the overall product.

2.7 Document validated KCs, KC flowdowns, KC classification and supporting information: All results from assessment must be documented to support mitigation and reuse/legacy purposes.

Supporting practices: KC Tracking Forms, FMEA Reports, QFD Reports, KC Management Plans and KC databases can capture assessment information. As stated for procedure 1.8, documentation practice(s) must be consistent throughout all VRM stages.

7.2.3 Mitigation Stage Procedures

Figure 15 illustrates the sequence of procedures required for mitigation.

3.1 Review assessment information: Assessment results indicate the expected risk and causes of this risk. Review of assessment results ensures mitigation strategies are consistent with the risk level.

Supporting practices: CFTs are involved in the review of assessment information; these activities are often scheduled during product-process design reviews/validation. Historical Data may provide added information on existing or previously used mitigation strategies.

3.2 Assign mitigation responsibilities and update coordination plan: Mitigation must be a collaborative process between all impacted group to reach a decision of cost-effective mitigation strategies. The coordination plan must be updated based on assessment results (i.e., impacts of variation, impacted systems, sources of variation, system interaction/relationships, etc) to ensure all required CFTs and organizational functions are involved in mitigation strategies. On large-scale developments, multiple CFTs need to be involved during mitigation.

Supporting practices: Product-level CFTs are involved in assigning mitigation responsibility and updating the coordination plan; these activities are performed in alignment with the CFT

structures and/or product architecture. Responsibility Matrix and KC Management Plans define and record requirements for this procedure.

3.3 Select mitigation strategies (i.e., design changes, process changes, process improvements or measurement/inspection): One or a combination of strategies can be selected for mitigation. Selected strategies must be based on assessment information (probability of failure, cost of failure, cost of control and overall risk) and should be in the best interest of all impacted groups (i.e., design, manufacturing, suppliers, manufacturing, assembly, quality control, etc.).
Supporting practices: Product-level and lower-level CFTs are almost always involved during mitigation alternative selection; these activities are generally scheduled through product and process design reviews/validation. Historical Data can be considered for existing mitigation strategies and their effectiveness. QFD (Production/Quality Control Matrix) helps structure and records the selected mitigation strategy. Design and Process FMEAs structure mitigation selection and capture mitigation information. Cost/Loss Functions, and Operating Window Concepts can support this procedure by graphically illustrating expected loss due to variation.

3.4 Evaluate impact and cost of strategy to overall product and confirm mitigation strategies (collaborative decision): All selected mitigation strategies must be confirmed by evaluating impact and cost of strategies to the overall product. KC flowdowns and VRM documentation are be helpful when confirming selected mitigation strategies.
Supporting practices: Product-level and lower level CFTs must be directly involved with mitigation alternative selection; this procedure is often scheduled through product-process design reviews/validation. Operating Window Concepts and Cost/Loss Functions help evaluate expected loss due to variation. KC Flowdowns (KC Trees) reflect KC relationships/interactions, which are necessary when determining impact on the overall product and selecting the most effective control/inspection points. Sensitivity Analysis and Feasibility Studies provide information to justify and validate mitigation strategies. Process Flow Charts and Product-Process Interaction Techniques reflect interactions between the product and process that must be considered for measurement/inspection strategies.

*3.5 **Design change or process change (yes/no decision):*** Mitigation strategies involving design and process changes may require the changes to be reviewed by identification and/or assessment stages. All other strategies should not require these steps to be repeated.
Supporting practices: CFTs must review the selected mitigation to determine which design and process changes require identification and/or assessment to be repeated.

*3.6 **Establish control plans (measurement, inspection, and corrective actions) and/or continuous improvements plans:*** Control plans and/or Continuous Improvement Plans must be developed to support all KCs sent to production while still considered at risk. These plans can include Pre-production Control Plans, Production Control Plans, and Continuous Improvement Plans. Pre-production Control Plans should define special prove-out and/or production ramp controls. Production Control Plans (dynamic (can be removed) and continuous (must remain in place)) define all measurement and inspection requirements for products and processes. Continuous Improvement Plans require applied measures to improve production processes, but may or may not require formal controls. All KC mitigation strategies must be clearly documented as to their immediate and long-term requirements.
Supporting practices: Pre-production Control Plans, Production Control Plans (dynamic and continuous), Continuous Improvement Plans and the procedures used to develop these coordination plans are the most common methods to support this procedure. Statistical Process Control (SPC) practices are used in conjunction with the control procedures to monitor and provide feedback on process capability. Production Process Validation and Process Acceptance Requirements are often established to require feedback on production process capability and control prior to or during production; these requirements are used to ensure compliance with control and improvement plans.

*3.7 **Document mitigation results:*** All mitigation results must be documented to support traceability, troubleshooting and reuse purposes. All documented control plans and continuous improvement plans must be transferred to production and quality control groups.
Supporting practices: KC Tracking Forms, KC Flowdowns (KC Trees), FMEA Reports, QFD Reports, KC Management Plans, KC databases, Control Plans and Continuous Improvement Plans capture mitigation information.

7.3 Guideline Summary

The proposed guideline describes a complete VRM process. The prepared sequence of procedures was developed in conjunction with the assessment basis, defined in Chapter 2, which was established based on a complete VRM process perspective. A final evaluation was performed with the assessment baseline to confirm all VRM requirements and activities outlined in the assessment baseline (see Chapter 2, sections 2.2.5 and 2.3.4). Although the VRM guideline has been confirmed with the assessment basis, onsite implementation should be used for final VRM process validation.

Although supporting practices have been listed for each procedure, the implemented set must be based on the company's VRM objectives and specific application requirements. Before implementation of these supporting practices, it is recommended that companies select a set of practices that work best for their application and then ensure they are aligned for the overall VRM process. This alignment must guarantee all procedures are executed and information is consistently managed between procedures.

8 Concluding Remarks

The author initiated this research based on the hypothesis that discontinuities exist in most VRM processes. These discontinuities are believed to be results of VRM implementation activities that have focused only on specific problem areas while overlooking the overall VRM process activities and requirements. This has led to implementation of incomplete or fragmented VRM processes and the use of poorly aligned supporting practices. Assessments of three company's VRM processes were used to validate this hypothesis. Assessment results indicate that discontinuities do exist and there is often poor selection and alignment of supporting practices for and between VRM stages. A series of problems have been identified for which the VRM guideline was developed to help resolve or avoid. These problems include poor follow-up of identification with assessment and mitigation, no complete processes that addresses VRM in its entirety, limited explicit management of VRM information and incomplete supporting processes to address all required VRM procedures.

Inadequate execution of assessment and mitigation was a common problem observed with current VRM applications. In many situations identified KCs are transferred directly to mitigation without sufficient assessment of potential KCs. Without proper assessment, information required for effective mitigation is not available. This information (probability of failure, cost of failure, impact of failure, source of variation and KC interactions / relationships) is vital for determining the sources of variation, impact to the overall product and most effective means to control KCs. Poor assessments often lead to ineffective mitigation strategies. Poor allocations of control resources, redundant measure requirements and over burdened control plans are all potentially resulting problems. The guideline encourages a continuous, systematic process where identification is followed up with clearly established assessment and mitigation activities; this approach to VRM should help resolve inadequate assessment and mitigation practices.

Few existing processes establish coordination plans for VRM activities that align with the overall product. In many situations individual CFTs or organizational functions perform VRM for specific portions of the design, but few measures exist to ensure it is executed from an integrated

product perspective. Coordination of VRM must be established upon the start of VRM activities to ensure the most cost-effective mitigation strategies are available. Clearly defined responsibilities for all involved CFTs and organizational functions are a necessity to ensure VRM is properly executed and coordinated for the overall product. The guideline requires CFT structures and product architecture to be determined in advance. Coordination plans can then be established based on this information.

Existing VRM processes generally do not manage KCs and KC information explicitly[20]. This observed problem impacts effective VRM execution as well as reuse of KC information. Central to this problem is that KC flowdowns are not clearly established. KC flowdowns must be prepared to identify source(s) of variation, product level impact(s), relationships and interactions between KCs, vital to identification, assessment and mitigation. Because KCs and KC information is not explicitly captured, KC classifications and supporting information is not always accessible. Classifications and supporting information is vital when identifying the expected risk used to prioritize assessments and mitigation activities. Documentation and communication of VRM information are procedures in the VRM Guideline that help ensure VRM information is explicitly managed. These procedures guarantee VRM information is always made available for proper VRM execution and reuse purposes.

Selection and utilization of supporting tools and techniques is not always adequate for proper application of VRM. Part of this problem is related to a lack of understanding regarding dependencies between VRM stages. Objectives along with inputs, procedures and outputs must be clearly defined for the overall VRM process. When these requirements are clearly established, supporting practices can be properly selected to meet the VRM requirements. In several existing VRM processes, specific requirements for the process are not clearly defined. This has resulted in uncertainty as to what must be accomplished for each VRM stage and what should be completed as KCs advance through the VRM process. The VRM guideline has been developed to clearly reflect requirements for each VRM stage. Each stage starts with a review of

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[20] Explicitly implies that KC and VRM information is managed with specific practices rather than through practices that are intended for other information.

supporting information that is intended to reveal exactly what supporting practices should be used for proper KC management. The VRM guideline does not define specific practices to be used, but rather suggests options that can be selected based on specific applications.

Most existing VRM processes suggest supporting practices that are not always aligned with the overall VRM process. As a result, there are no clear links between supporting practices required for all procedures or information exchange. These problems have been observed as poor alignment between CFT activities, CFT structures and product architectures. They are also observed as poor links between individual FMEAs and Control Plans. To ensure effective and complete execution of VRM, it is recommended that a set of practices be required based on expected applications of the VRM process. This selection must be based on specific company requirements for the overall VRM process. The selected set of practices must ensure each procedure is properly supported and the complete set is aligned for overall VRM application. In most situations, the actual sets of supporting practices differ slightly across companies, but the overall VRM process should be the same. As a result, each company must select and optimize a specific set of practices for their VRM application. The supporting practices defined in the VRM guideline provides possible alternatives that can be consider for this set.

The Massachusetts Institute of Technology Key Characteristic Research Group plays a vital role in the continued development of the VRM guideline and advancement of supporting practices. This group has ongoing interactions with industries that help test and validate the improvements suggested by this thesis. Extensive research is focused on tools to establish KC flowdown models and to support documentation and communication of KC information. Additional research activities focus on application of VRM for a wide variety of product and production volume industries. In addition, continued use and refinement of the assessment basis increases understanding of VRM applications. Case study applications and evaluation of the VRM guideline can help validate and refine the proposed process.

Appendix A

Product Development Space Imposed VRM Requirements
Identification
• Identification must review all product levels for potential KCs. • Identification activities must encourage all organizational functions to evaluate designs for potential KCs. This identification should be performed by both Cross-Functional Teams and individual organizational functions. • Identification must determine relationships between product-level requirements/impacts and sources of variation with use of a KC flowdown. • Identification should be coordinated between organizational functions. • Identification should be completed for each phase of the development starting with early development phases. This requirement ensures KCs are identified for assessment/mitigation before the product advances to later development phases. • Identification must exchange information in a format that supports documentation and communication functions. This format should clearly reflect traceability, classification, flowdown and other information that is required during assessment and mitigation.
Assessment
• Assessment must review and refine identification information (potential KCs and KC flowup/down). • Assessment must consider information from individual levels and/or systems of the product that will/can be impacted by KCs. • Assessment must obtain inputs/information necessary for assessment from multiple organizational functions (internal and external) and/or through Cross Functional Teams. • Assessment must exchange information in a form that supports documentation and communication.
Mitigation
• Mitigation should consider multiple product levels during mitigation selection. • Mitigation must be a collaborative decision between multiple organizational functions (internal and external) and/or Cross Functional Teams. • Mitigation must consider information provided from identification and assessment activities. • Mitigation must obtain and provide information in a form that supports documentation and communication. This requirement ensures that all mitigation activities are justified and clearly understood for reuse or troubleshooting measures.

Documentation and Communication
• Documentation and Communication must support exchange of information throughout and between developments. This requirement ensures KC information is available and accessible to all developments. • Documentation and communication must support exchange of information between primary VRM stages/functions. • Documentation and Communication must capture information necessary for reuse/legacy data.

Appendix B

Key Characteristic Symposium Summary Statements	
Stated Customer Needs	**Defined Process Requirements**
Identification	
• New technology is robust when it is introduced • Guidelines for high level KC identification • Imbedded in functional and product definition • Clear link from piece part KCs to sub-assembly to system to customer satisfaction • Switch to performance variation tools from dimensional variation tools • Product focused through build and support • Consistent flowdown for all groups is not done • Initiative overload	• Identification should consider new technology for potential KCs • Identification must define the relationships between top-level product requirements and the source of variation • Identification must evaluate both functional and dimensional parameters of the product for potential KCs • Identification process must start as early in the development process as possible and continue through all development phases • Identification should ensure only that the vital few parameters that require special attention are selected for assessment
Assessment	
• Validation Testing • Performance based acceptance • Focus should be on process, not parts • Need metrics or exit criteria	• Assessment must be used to validate potential KCs before they are considered for mitigation • Assessment should be based on quantitative information whenever possible • Assessment should consider both functional and dimensional criteria
Mitigation	
• Appropriate measurement plans in production • Now the processes are focused on driving out variation rather than robust design • Minimum number of KCs	• Mitigation activities must be linked directly to control and measurement plans • Mitigation activities must consider improving the design, ensuring robust designs, as a method to minimize the impact of variation • Mitigation should work to minimize the number of KCs

Communication, Documentation and Documented Instructions	
• Poor communications between interfaces (vendors, functions and customers) • Process definition is not clear • Ability to communicate supplier capability • Standard KC callout must be established • Vision and Goals are not clearly expressed • Clear definitions • KCs need to be a well-understood part of the design process • Reliability of KC measurement both internal and external suppliers (measurement accuracy, discipline) does not exist • Lack of clear expectations for excellence in execution • Training not clear enough • Process definition not clear • Take known process capabilities and KCs and use/reuse them with efficiency • Flowdown of requirements is not done well	• Documentation and Communication must ensure coordination between organizational functions • Documentation and Communication must support the flowdown and traceability of requirements/information for KCs • Documentation and Communication must provide process capability feedback for the identification, assessment and mitigation functions • Documented instructions should have standards to ensure consistent capture, distribution, interpretation and reuse practices. • Documented instructions must have clearly defined goals and objectives for the VRM process • Documented instructions must ensure a consistent set of definitions and/or classification are established and used • Documented instructions should clearly outline expected reactions and/or implications for identified KCs • Documented instructions should outline the relationship between the VRM process and the product development process.

MIT Key Characteristics Maturity Model					
Practice	**Level Definitions**	**0 Not used at all**	**1 Reactive**	**2 Semi-Proactive**	**3 Fully Proactive**
KC Identification Stage	The phase in which KCs are identified.	None identified.	KCs identified in production when quality problems occur. Triggers for identification of KCs include high rework, scrap, repair or customer dissatisfaction.	KCs identified at the end of product design (after the design is completed but before the design is put into production). These KCs identify areas of potential cost and require extra control by manufacturing to ensure a quality product.	KCs identified during the early stages of design and are continually updated. They are identified where the design is not robust for the current manufacturing capabilities. Efforts are made to reduce the risk associated with KCs.
KC Definition	The existence of common definitions and methods within and between groups.	Not clearly stated.	KCs are defined by the teams identifying and using them. No consensus or communication between functional groups about the criteria for identification or the implication once identified.	A common definition is documented but variability exists between groups.	A common manageable set of understandable definitions and classifications exist. Common understanding of what a KC is and what it means.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
KC Prioritization	The process by which a set of KCs are ranked according to their importance.	None.	KCs are ranked according to high cost of rework, scrap, or repair costs.	Qualitative ranking system based on assumptions of potential problems.	Ranking based on quantitative measures including historical process data and models.
KC Validation	The process by which the selection of the correct KCs is verified.	None.	The set is considered valid if a reduction in rework, assembly hours, productions cost is seen.	Modeling is used at the end of the design process to identify areas where there is a potential risk . The identification of the correct set is validated by problems seen once in production.	Early use of prototypes and virtual models to ensure that the correct set is identified. Uncertain processes are validated prior to full production.
Documentation	The formal documents and processes by which KCs get transmitted between groups (e.g., design,	None.	KC information is scattered across a variety of functions with no centralized source.	KC information is documented, but not easily accessible. Only major design changes trigger KC updates.	Identified KCs are well documented and traceability is established. All KCs and supporting documentation are updated regularly.
KC Flowdown	The process by which KCs are decomposed from a system or customer level to a piece part level.	None.	Features at a piece part are identified as critical without linking them to a fit, performance or system-level	System-level KCs are understood. Piece-part level features are identified based on a non-traceable linkage with the system KC.	Coherent flow from the customer requirements, through sub-assembly, to feature levels with clear traceability.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Modeling	The computation and quantitative methods by which a product is evaluated. The models can be capable of measuring performance, effects of variation, and	None.	Modeling used if problems in production occur.	Variation modeling used at the end of the design cycle to check where problems may occur.	Variation modeling used early in the design stages. The models are continually updated and design alternatives are considered to remove potential problems.
Customer Interaction	The ongoing interaction between the customer and the product development organization.	Minimal interaction.	Customer interaction conducted when repeat product rejections occur.	VOC is understood and flowed down to the designers. However, the impact of current capability on requirements is not explicitly addressed.	VOC is flown down and the ability to achieve it is continually evaluated.
Integrated Product Teams	The cross-functional teams that are used to develop the product.	None.	Formed when there is a problem in production.	Formed during the product development process. They react to potential problems in fire-fighting mode.	IPTs are formed at the start of the design process. They have a clear set of objectives and proactively attempt to find and eliminate problems before they arise.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Supplier Interaction	The interaction between the supplier and the product development organization.	Drawings and designs handed over the wall.	Suppliers brought in only if a problem occurs.	Suppliers are brought in at the end of the design to verify the producibility.	Suppliers are integrated with the IPTs to evaluate producibility. They make suggestions where the design may not be robust and where relief in requirements will have a significant impact on cost.
Management Support	The leadership, resource allocation, and role that management needs to play to enable good KC use in the organization.	Not Applicable.	Mgmt. encourage the use of KCs but resources are not properly allocated.	Mgmt. supports engineering teams to use KCs, but KCs are ignored if larger problems arise.	Mgmt. understands the need for KCs and they advocate and help facilitate their use within the company.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Incentive Structures	The organizational drivers that encourage the use of KCs and the resulting level of willingness of the product development team to participation in the methods and supporting practices.	None.	Forced by contractual or management requirements and performed as a box checking exercise.	Performed as a separate, independent process that requires people to "put KCs on drawings" but not at the expense of drawing release. Some benefits of KC utilization are acknowledged.	Incentives to effectively put KCs on drawings. KC practices are fully accepted and performed as a seamless, integrated process. The processes are seen and demonstrated as an enabler to achieve both low cost and robust designs.
KC Training	The formal courses, documentation, and ongoing training that an organization offers and supports.	No training program.	Documents about KCs given to engineers and suppliers. They are told to "do KCs" without training.	Training is done but the examples are not applicable to realistic design areas. No follow-up or long term assistance is performed to ensure understanding or proper use.	Program are developed to increase skills in design and manufacturing. Training occurs "just in time." Training addresses, through real examples, the problems that teams are facing. Follow-up training and coaching available to ensure proper application.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
KC Objectives	The stated goals and needs that define the scope of the KC effort.	No stated goals	Goals are to reduce cost in current production.	Goals are to identify high cost and high risk areas before the product is transitioned into production.	Goals are to reduce cost, risk, and time-to-market through front-end attention to areas of low robustness, high cost, and high risk. These objectives are clear throughout the extended enterprise.
Measurement Plans	The quality control plans implemented by the manufacturing organization to control and track variability throughout the life cycle of the product.	No measurement plans.	Measurement plans implemented to solve problems identified during production.	IPTs set measurement plans based on KCs resulting in too large of a set of measurement points. These measurement points are not changed as processes are validated.	KC driven measurement plans used to validate where 1) capability prediction is uncertain and 2) design is not robust. Plans change through the life of the product as processes and products are validated.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Process Capability Feedback	The process by which historical data on process capability is made available to functional organizations outside the manufacturing group.	No feedback into design.	Capability fed back when problems occur.	SPC data captured and recorded for a variety of features, but data is hard to find and isn't used throughout the organization.	SPC data fed back to design, updated, and is available electronically in a form that is painless to use.
Process Capability Uncertainty	Systematic identification and reduction of uncertainty in the process variability.	No measure of uncertainty.	If a problem occurs in production, measurements are imposed to reduce uncertainty.	Uncertainty in process capability is acknowledged and discussed. A manufacturing plan is put in place before production begins to reduce uncertainty.	Team has a system view of capability uncertainty and deploys effective control plans to maintain quality and work toward process improvement.
Design Changes / Robust Design	Design modifications due to an inability to achieve the function of the systems at a reasonable cost.	None.	Late design changes are made to reduce significantly high production cost.	Reactive changes are made to areas that are found not producible during production ramp-up.	Changes are made by design and manufacturing during the design stage by means of an iterative design process to increase producibility.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
New Technology Introduction	New technology (product and process) is introduced, when it is robust, into a product development environment.	No new technology is introduced or no reaction occurs to problems caused by new technology.	Problems with new technology addressed during ramp up and production.	Failure modes are identified before product launch and monitored or tested out.	Technology robustness issues are identified prior to product development, design decisions and control plans are utilized to ensure robustness of the final product.
Cost Models	The ability to understand and quantify the cost implications of design decisions.	Not measurable.	Able to identify the high cost or rework, repair, and scrap (RR&S) once in production. Unable to quantify these costs accurately.	Identify potential high cost of RR&S in the development stage.	Costs are used to identify where changes in design should occur. Able to tradeoff the costs of redesign vs. inspection and rework.
Reuse/Legacy Data	The ability to leverage and utilize existing product data and document as well as maintain new design documents in a form that is reusable.	KCs are re-identified and legacy data is not considered.	KCs are reused only when conditions are considered identical.	Reuse is limited. Legacy data is randomly updated and generally unstructured.	The product/process relationships are understood and the KC data is maintained, updated and reused where applicable.
Tolerancing & Dimensioning	The consistent application of good tolerancing practice.	Not considered. GD&T not used.	Tolerance based on old designs. GD&T applied randomly.	Reviews used to ensure correct and consistent use and application of GD&T.	Automated systems throughout the organization to ensure consistent application of GD&T.

Appendix D

VRM Requirements based on the MIT KC Maturity Model			
Element	**Definition**	**Area of Concern to VRM Guideline**	**Imposed Objectives or Requirements**
KC Identification Phase	The phase in which KCs are identified.	Identification	• Identification must start early in the development process and continue through all development phases • Identification should work to validate the robustness of the design
Supplier Interactions	The interaction between the supplier and the product development organization.	Identification Assessment Mitigation	• Identification must be coordinated with suppliers (internal and external) • Assessment must be coordinated with suppliers (internal and external) • Mitigation must be coordinated with suppliers (internal and external)
KC Flowdown	The process by which KCs are decomposed from a system or customer level to a piece part level.	Identification Assessment Mitigation Documentation Communication	• Identification must determine the KC flowup/down for identified potential KCs • Assessment should confirm and expand the KC flowup/down • Mitigation should utilize the KC flowup/down during alternative selection • Documentation and Communication should capture the KC flowup/down for reuse
Customer Interaction	The ongoing interaction between the customer and the product development organization.	Identification Mitigation	• Identification must be linked to and motivated by (internal or external) customer requirements
Tolerancing & Dimensioning	The consistent application of good	Documentation Communication	• Documentation and Communication

	tolerancing practice.		must ensure tolerancing and dimensioning are used to ensure consistent and accurate KC interpretation
KC Definition and Methods	The existence of common definitions and methods within and between groups.	Documentation Communication	• Documentation and Communication must ensure that a manageable set of definitions and classifications are established and used
KC Validation	The existence of common definitions and methods within and between groups.	Assessment	• Assessment must use Qualitative and Quantitative assessments to validate all potential KCs
KC Prioritization	The process by which a set of KCs are ranked according to their importance.	Assessment Mitigation	• Assessment should prioritize validated KCs before mitigation • Mitigation should prioritize validated KCs that are to be controlled
Documentation	The formal documents and processes by which KCs get transmitted between groups.	Documentation Communication	• Documentation and Communication must ensure that supporting documentation and training material exist to direct the VRM process
Modeling	The computation and quantitative methods by which a product is evaluated. The models can be capable of measuring performance, effects of variation and potential failure modes.	Assessment	• Assessment should include the use of models whenever possible to support quantitative assessments
Integrated Product Teams (or Cross-Functional Teams)	The cross-functional teams that are used to develop the product.	Assessment Mitigation	• Assessment should use integrated product teams to support the organization focused interactions • Mitigation should use integrated product teams to support collaborative alternative selection

Management support	The leadership, resource allocation, and role that management needs to play to enable good KC use in the organization.	All Functions	• All functions must have proper management support for proper execution
Incentive Structures	The organizational drivers that encourage the use of KCs and the resulting level of willingness of the product development team to participation in the methods and supporting practices.	All Functions	• All functions should use incentive structures to encourage application
KC Training	The formal courses, documentation, and ongoing training that an organization offers and supports.	Documentation Communication	• Documented instructions must provide material to support VRM training
Objectives	The stated goals and needs that define the scope of the KC effort.	Documentation Communication	• Documented instructions must reflect clear objective for the VRM process
Measurement Plans	The quality control plans implemented by the manufacturing organization to control and track variability throughout the life cycle of the product.	Mitigation Documentation Communication	• Mitigation must be tied directly to the control and measurement plans to ensure proper long-term and short-term control of validated KCs • Documentation and Communication must ensure information exchange necessary for the measurement plans
Capability Feedback	The process by which historical data on process capability is made available to functional organizations outside the manufacturing group.	Assessment Documentation Communication	• Assessment should use capability feedback information whenever possible • Documentation and Communication must ensure information exchange supports capability feedback
Capability	The level of uncertainty	Assessment	• Assessment must compensate for

Uncertainty	about the process variability in a manufacturing process due to changing processes or new designs.	Mitigation	capability uncertainty
Robust Design	Design modifications due to an inability to achieve the function of the systems at a reasonable cost.	Assessment Mitigation	• Assessment should help to confirm product robustness • Mitigation should select alternatives that encourage robust designs whenever possible
New Technology	New technology (product and process) is introduced, when it is robust, into a product development environment.	Identification	• Identification activities must consider New Technology as a source for potential KCs
Cost Trade-Offs	The ability to understand and quantify the cost implications of design decisions.	Mitigation	• Mitigation activities should consider the cost of the alternative versus the cost of variation when considering all alternatives
Reuse/Legacy Data	The ability to leverage and utilize existing product data and documents as well as maintain new design documents in a form that is reusable.	Documentation Communication	• Documentation and Communication must capture information necessary for reuse/legacy data

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