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More than Just Robust Design: Why Product Development Organizations Still Contend with Variation and its Impact on Quality

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Abstract. *Current market conditions require design and manufacturing companies to continually increase product functionality, reduce design cycles, decrease cost and improve quality. One way to improve quality is to minimize the impact part and process variation has on final product quality. Although companies know they must reduce variation, they are still struggling with executing coherent variation management strategies. To understand why companies still fail to systematically address variation, an ideal model of variation management is proposed, entitled* Variation Risk Management *(VRM). This model was used to assess the state of industry practice. These results are compared to the current literature available on the subject. It was found that many problems with industry implementation are due to a lack of quantitative models that enable a design team to make quick and accurate decisions. This paper concludes with a list of interesting challenges facing the VRM field.*

Keywords: Industry practice; Quality; Variation management

1. Introduction

Design and manufacturing firms are under significant pressure to simultaneously increase product functionality, reduce design cycles, decrease cost and improve quality. One way to improve quality is to minimize the impact part and process variations have on final product quality. Authors such as Taguchi (1993) and Deming (1986) have provided strong arguments about the detrimental effects of variation. In addition, there has recently been significant publicity about GE, AlliedSignal and Motorola's successful use of *Six Sigma* – a systematic method for reducing variation and improving quality. It is the authors' experience that most companies understand that variation creates cost, and that efforts to reduce variation through better design or better processes will reduce their costs. Although companies understand they must reduce variation, companies are still struggling with executing coherent variation management strategies (Jay 1998; Ueno 1995).

To help understand why companies still fail to systematically address variation, an ideal model of variation management is proposed entitled *Variation Risk Management* (VRM) (Jay 1998; Thornton 1999). This model is used as a benchmark, against which current industry practice and academic literature are compared. VRM is a systematic method to identify, assess and mitigate variation throughout the product development process. The new term VRM is used because the existing variation frameworks are not easily integrated (i.e. Taguchi methods, 6 Sigma). The VRM framework draws from many bodies of literature and provides a coherent structure in which diverse practices can be simultaneously evaluated. The VRM framework is supported by 22 industry practices. A practice is a set of methods that can be used to address one portion of the variation problem. A practice can also include supporting methods such as management support. For each practice, four levels of implementation maturity were identified. This model allows industry to assess their level of implementation and benchmark their processes against other industries. In order to understand the current state-of-the-art in industry, a survey of 19 companies was done and the academic literature reviewed for twelve of the supporting practices[1]. The 19 companies represent a range of technologies and products. The objective of this paper is to assess both current industry practice and current research in academia to identify what topics require further research and development.

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[1]Due to space constraints, only a subset of the most important practices were included. The survey results for the other ten practices can be found in the Master's thesis by Ertan (1998).

First, the VRM framework (Section 2) is described. Then, the survey method is reviewed (Section 3). Finally, the twelve of the practices supporting VRM are described along with the survey results, the relevant literature, and an analysis of barriers (Sections 4–7). In addition, a short summary of survey results for the other practices is included (Section 8). The paper concludes with a list of problems that should be addressed by the design, manufacturing, and management research communities (Section 9). If addressed, research in these areas will improve a design/manufacturing organization's ability to systematically identify and reduce the impact of variation.

2. Variation Risk Management Framework

Variation risk management is the process of continually identifying, assessing, and mitigating variation risk. Variation risk is the probability manufacturing processes will effect final product quality and the cost of that failure. Variation risk management is a three-step process: the potential risks are identified, relative risks are assessed, and then risk is reduced through mitigation strategies. These steps should be iterated throughout the design process. Table 1 shows the practices reviewed in this paper that support each VRM stage.

2.1. Risk Identification

Risk identification (also called Key Characteristic identification) is a two-step process: risk identification and risk flowdown. Risk identification collects the variation-sensitive requirements. Risk flowdown is an iterative decomposition process that identifies a hierarchy of contributing assembly, subassembly, part and process parameters. These risk factors are

Table 1. VRM practices

Identification	Assessment
VRM initiation	Variation Modeling
Quantification of Customer Requirements	Capability Feedback
Key Characteristic Flowdown	Capability Uncertainty
Mitigation	**Supporting**
Manufacturing Quality Plans	Documentation
Robust Design	Supplier Relations
Cost/Benefit Tradeoffs	Management Support

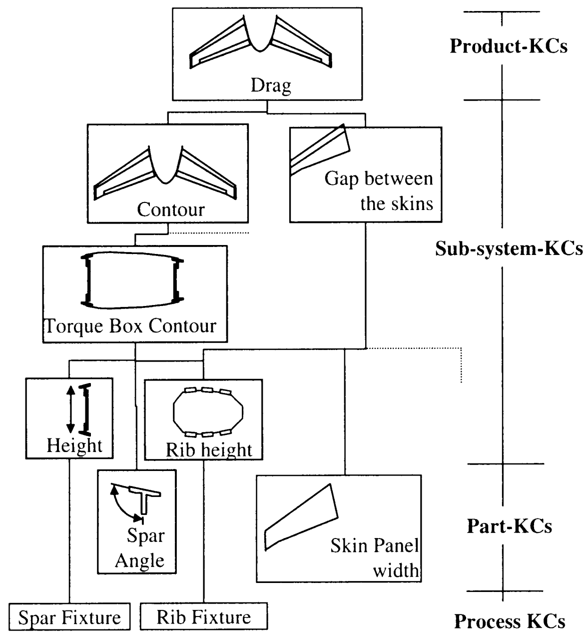

Fig. 1. KC flowdown.

often termed the *Key Characteristics* (KCs) of a product. Organizations using KCs include Boeing, GM, Xerox and ITT. Although KC terminology and implementation schemes vary between corporations, the organization-specific methods have common goals. KC processes identify the small set of critical features for an organization to focus on during design and manufacturing (Lee and Thornton 1996)[2].

Figure 1 shows a part of the KC flowdown for aircraft wing drag. The product-KC (i.e. drag) is at the top of the tree and has several contributing subsystem-KCs (i.e. contour and gap). These, in turn, are a function of part-KCs (i.e. spar angle) and process-KCs. The KC flowdown provides a system view of variation risk factors and captures the design team's collective knowledge of variation-sensitive requirements and their contributors. Flowdowns are generated through interviews, analysis of tolerance chains, and analysis of failure modes. A typical flowdown contains many more layers and KCs than the example shown. For example, a 100 part medical product has about 600 elements, a single join in an aircraft has about 25.

The risk identification stage is supported by three practices: VRM initiation, quantification of customer requirements, and KC flowdown. VRM initiation is the stage in the design process when variation

[2]All of the literature on Key Characteristics resides in company documentation. There is little literature, other than that by the author, on the subject.

identification begins. Quantification of customer requirements sets targets and latitudes for customer requirements/Product-KCs. KC Flowdown is the systematic process used to identify the subsystem-, part- and process-KCs that contribute to the product-KCs.

2.2. Risk Assessment

To optimally control, reduce, and remove variation it is not necessary to address all of the KCs in the KC flowdown. To determine the critical subset, risk must be assessed using one of two methods: bottom-up or top-down (Rivest et al.1994). *Bottom-up* uses product models to predict the final product quality from individual process variations. Given the predicted variation, risk is the expected loss incurred when quality targets are not achieved. The expected loss can be calculated using Taguchi's (1993) quadratic loss function or using a step function (Thornton 1997). The *top-down* approach allocates the allowable variation to individual features in the form of tolerances. Risk is assessed by comparing the tolerances on individual features to the expected variation using either *Cpk* (Srinivasan and O'Connor 1994; Zhang and Fang 1996) or defects per million (DPMO).

In many cases, it is not possible to predict variation and costs exactly. Early in the design process, product models and predicted process variation data have a high degree of uncertainty and this uncertainty can significantly affect action taken in subsequent stages.

The assessment stage is supported by three practices: variation modeling, capability feedback, and capability uncertainty. Variation modeling are the tools used to predict the final product quality from the part and process variations. The process capability for an organization's manufacturing systems should be captured and made available to design. Process capability data should then be used to populate the variation model. Finally, a measure of capability uncertainty is required to understand the bounds on the variation model.

2.3. Risk Mitigation

Most commonly used tools fit into the category of risk mitigation. Mitigation strategies fall into two broad categories: design changes and process improvements. Design improvements include robust design and the specification of higher quality parts and processes. The second method reduces variation by improving existing manufacturing processes through manufacturing quality plans. Quality plans can include process improvement, SPC or inspection. Process improvement adjusts current processes to reduce input variation. Statistical Process Control (SPC) monitors ongoing processes to prevent process degradation. Inspection is used to identify parts that should be scrapped or reworked.

Risk mitigation is supported by three practices: cost/benefit tradeoffs, robust design, and manufacturing quality plans. The cost/benefit tradeoffs are the tools used to identify where mitigation will be most effective. These methods also enable teams to choose between mitigation strategies: robust design or manufacturing quality plans.

2.4. Practices Supporting the Entire VRM Process

In addition to the identification, assessment, and mitigation practices, several practices support the entire process. These include documentation, supplier relations, and management support. Documentation is used to record the product development information associated with the VRM process. Good supplier relations are needed to support VRM in the extended enterprise. Finally, management support is needed to allocate the resources, schedule, and incentives to implement VRM practices.

3. Research Method

As stated above, 22 practices were found to support the VRM process. The selection of practices was based on interviews and case studies of over thirty industries and their variation management practices. Lists of tools and methods were collected and the common elements synthesized into the 22 practices presented in this paper. The practices were reviewed with company experts to ensure complete coverage. In addition, the current literature in the field was surveyed and grouped by practice. About five iterations were made to the model before the survey was undertaken.

To assess a company's variation risk management process, four levels of implementation maturity were identified for each practice: none, reactive, semi-proactive, and fully proactive (Table 2 shows the four maturity levels for the practice *VRM initiation*). Textual descriptions for each level were developed based on the industry interviews and literature.

When a company does not exercise the practice, it is given a level zero maturity. Reactive (i.e. level 1) practices are performed when there is a production

Table 2. Maturity level for *VRM initiation*

	0: Not used at all.	1: Reactive	2: Semi-proactive	3: Fully Proactive
VRM initiation: The phase in which VRM is started.	(0) KCs never identified	(1) KCs identified when quality problems occur in production	(2) KCs identified at the end of product design where extra control is required.	(3) KCs identified during the early stages of design and are continually updated.

problem, rework repair, scrap, or low yields. Semi-proactive (i.e. level 2) practices are performed late in the design process. They are used to improve the product as it is transferred to manufacturing. Fully proactive practices (i.e. level 3) are performed continuously during design process. Each level corresponds to an implementation practice we observed in industry. No company performed at a level 3 for all practices. We did observe at least one company implement each level three practice. The practices and levels were validated through an informal review process with the interviewed companies.

The collection of VRM practices and their implementation maturities was used to survey a variety of design and manufacturing companies. Industry experts from 19 companies were asked to rank their organization's variation management practices (for larger organizations, more than one expert was asked).The companies represented a range of products and technologies. They all were 'large' organizations. The selection of industries was based on those companies that are likely to gain major benefit from implementing variation management techniques while having the infrastructure to implement standard practices.

Experts included the people responsible at each of the companies for the development and/or implementation of their VRM systems. The survey was given to the experts at an annual symposium on the topic. Because practices vary within a company, survey respondents were asked to put a percentage against each level of maturity for each practice. For example, 10% of the company may be a level zero maturity, 20% at a level one, 40% at a level two, and 30% at a level three.

To validate the data collected, we performed two in-depth assessments (two weeks of on-site work): one on a company producing imaging equipment and one producing military equipment. Our results were compared to the company responses. In general, the company experts were more optimistic about their maturity by about 0.5 of a maturity level but the distributions were consistent.

When the results were first tallied, all 19 surveys were averaged together[3]. However, the resultant standard deviations were quite high. On further analysis, it was found that there were two groups of survey results. The first group produced military and aerospace products (12) and consistently had lower maturities than the second group (7). The second group produced commercial products such as automotive and copier systems[4]. Even with the small population, the commercial group was statistically better than the aero/military group. A two population test (assuming different standard deviations) was done for all survey questions. All pairs were tested and the means were different with at least a 96% significance (most were 99%)[5].

4. Risk Identification

Three practices supporting risk identification are reviewed in this section: initiation, quantification of customer requirements, and KC flowdown. As stated above, the identification process has two stages: product-KC identification and flowdown of product-KCs to part-KCs.

4.1. VRM Initiation

Variation risk management should begin early in design. If identification is started early, design changes can be made at lower cost. For example, the Ford *Windstar* vehicle development team estimated up-front attention to variation saved between five and ten million dollars in downstream rework costs (Sweder 1995). Saeed et al. (1993) also found

[3]The percentages for each maturity level were first averaged then an expected value weighting was used to compute the mean values.
[4]This difference is not unexpected. Aerospace companies and military companies typically lag behind commercial products in the adoption of new product development practices. For example, the automotive industry had been using 3-D CAD for many years before Boeing adapted the use of Catia on the 777.
[5]The graphs in each section contain the means and their significance. The table in the appendix contains the estimates of the difference in means for a 95% significance.

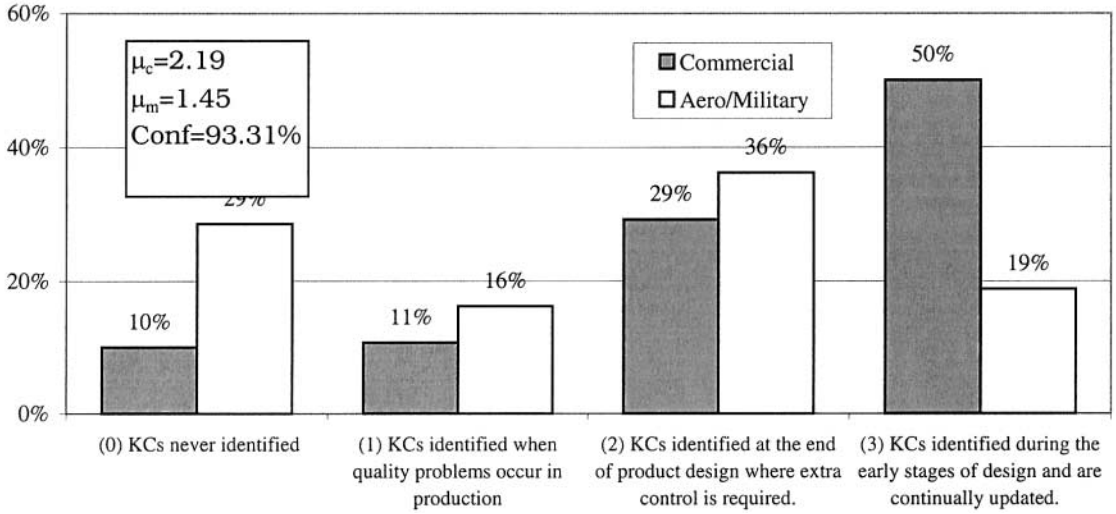

Fig. 2. VRM initiation.

that when manufacturing problems are not addressed in design, 5–6% of engineering's indirect labor is later spent fixing problems.

To assess when companies start VRM, we asked when KCs were first identified (Fig. 2). Despite the strong arguments for early initiation, a large portion of commercial product development projects delay initiation. The late starting point can be attributed to management not supporting VRM practices (Section 7.2) and/or designer's inability to identify (Section 4.2) and flowdown KCs (Section 4.3). In addition, many participants noted that VRM is resource intensive. Resource constraints may delay VRM until late in design when variation issues become more critical.

4.2. Quantification of Customer Requirements

Variation risk management starts by identifying Customer Requirements (CRs) that are sensitive to variation and quantifying the acceptable level of variation. The acceptable range of values around the CR target is termed the CR tolerance or latitude. The process of setting CR tolerances is sometimes termed functional tolerancing (Srinivasan et al. 1996). CR latitudes are used to assess whether or not the manufacturing processes are capable of producing acceptable quality.

A significant segment of CR literature is concerned with methods to identify needs and wishes. For example, Griffin and Hauser (1993) summarize a variety of CR collection methods. Another segment is concerned with turning CRs into technical specifications using tools such as House of Quality (Hauser and Clausing 1988) and Analytic Hierarchy Processes (Saaty 1980). Despite the plethora of research, a survey by Product Development Consulting (1996) pointed out that in most product development organizations customer requirements are *not* being systematically and effectively captured and communicated to the product development team. Dale (1997) attributes this failure to a lack of clear customer requirement measures; Bailetti and Litva (1995) to a lack of quality data about customers; and DiAngelo and Petrun (1995) to an inability to integrate customer feedback into design.

There is scant literature on systematic and quantitative methods to set CR tolerances. The literature on functional tolerancing is application specific; i.e. functional tolerancing for gears (Srinivasan, Wood et al. 1996) and bearings (Srinivasan and Wood 1997). Design latitudes are also considered in the reliability literature, but only to quantify minimum time between failures. Fuzzy sets are also being used to model the vagueness of CRs (Fung et al. 1998; Otto and Antonsson 1995; Temponi et al. 1997), but are typically used to calculate nominal targets. Figure 3 shows the survey responses for quantification of customer requirements. The lack of literature is consistent with industry practice. Commercial companies set targets but most do not set latitudes. Aero/military companies are not as mature with only 18% setting latitudes. In addition, companies use qualitative assessments rather than quantitative analysis to set CR latitudes.

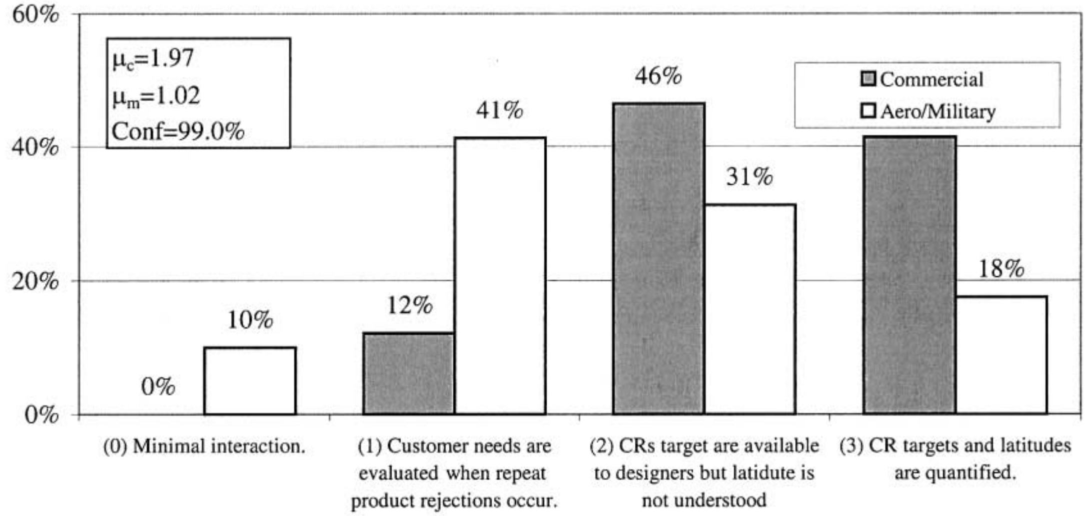

Fig. 3 Quantification of customer requirements.

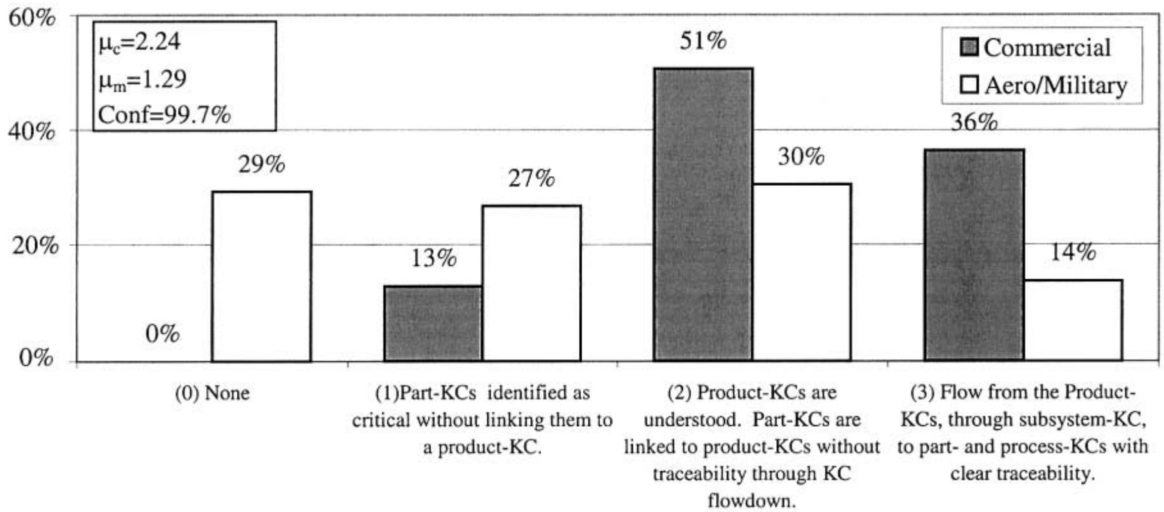

Fig. 4. KC flowdown.

4.3. KC Flowdown

KC flowdown is the process of linking product-KCs to part- and process-KCs. The flowdown creates a system view of variation that is needed for subsequent stages. Leyland (1997) describes difficulties faced during an automotive product launch[6] when the system view of variation was not communicated to the manufacturing plant.

Several methods are commonly used to identify KCs. House of Quality (Hauser and Clausing 1988) captures relationships between the voice-of-the-customer and engineering specifications and Extended House of Quality (Clausing 1995) flows specifications down to individual part features. House of Quality has three problems: it mixes variation-sensitive and non-variation-sensitive parameters, it is time consuming to generate, and it can be difficult to trace through the houses. Axiomatic design (Suh 1990) provides a similar systematic method for mapping functional requirements into physical design attributes but does not specifically focus on variation sensitive issues. Third, Failure Modes and Effects Analysis (FMEA) is used to track product failure modes, their causes, and effects. Practitioners we have spoken with often note the difficulty in tracing through FMEA charts. In addition, FMEA does not differentiate between failures caused by variation and those caused by operator error, design error, material failure, customer

[6]The process of bringing a factory up to full volume.

misuse, etc. Some organizations have developed their own KC flowdown methodologies and databases (Section 7.1). However, these methods are typically based on qualitative assessments and are not systematically applied.

Figure 4 shows the maturity of the KC flowdown process. On average, companies are not systematically identifying variation and its causes. Two problems contribute to this: the lack of flowdown and documentation methods (Section 7.1). The methods that do exist are very time consuming to execute and they do not exclusively look at variation issues. In most cases, companies who do not do a good job at flowdown tend to skip from product-KCs to part-KCs and process-KCs without creating a clear traceability through the product decomposition.

4.4. Summary

On average, commercial product development teams are semi-proactively (maturity level two) identifying variation. Risk identification is delayed until late in the design process, product-KC targets are quantified but latitudes are not; part-KCs are linked to product-KCs but not in a traceable manner. Aerospace companies average a 1.5 maturity and tend to be more reactive in their application of VRM practices.

Three areas need further research: understanding why risk identification is delayed and not integrated in the product development process, how to capture customer requirement latitudes, and how to systematically generate KC flowdowns. There is a strong argument for starting variation risk management early. However, common wisdom is not consistent with current practice. Delaying VRM is probably due to a lack of efficient, systematic, and quantitative methods for VRM practices. For both latitudes and flowdowns, there is a distinct lack of literature and methods. No systematic and low cost methods exist to quantitatively define customer requirement latitudes or flow requirements through subsystems, parts and processes.

5. Risk Assessment

As stated above, risk assessment is the practice of quantifying and prioritizing risk. Three VRM practices that support risk assessment are variation modeling, capability feedback, and capability uncertainty.

5.1. Variation Modeling

Variation modeling uses quantitative methods to predict how part and process variations impact customer requirements. Variation modeling is primarily used to predict out-of-tolerance frequencies, to identify the part and process features that contribute the most variation, and to evaluate design or process changes (Schmitz 1997). Ideally, modeling should be used throughout the design process. Models can range in complexity (Parkinson 1995) from simple linear models (Hendrix et al. 1996) to complex non-linear, simulation-based models (Kazmer et al. 1996).

Simple models may not capture the nuances of a complex problem, are subject to modeling errors, and are not easily maintained (i.e. they are built to answer a question, then deleted). Conversely, simple models can be used early in the design process when detailed models are impossible to build. Simple models can include root sum squared analyses and tolerance stack-ups. If the design problem is dimensional in nature, tolerance chains can be used to identify contributing dimensions (Cunningham et al. 1996).

Complex models can only be built when design details are close to finalization. They predict quality more accurately but are resource intensive to build, run and analyze. Application specific variation models are frequent subjects in the academic literature; e.g. injection molding (Beiter and Ishii 1996), printed circuit board production (Soyucayli and Otto 1998), LCD production (Lee and Joneja 1997), and compliant assemblies (Sellem and Riviere 1998). Variation Systems Analysis (VSA), a commercial software system, uses a Monte-Carlo simulation to model variation in assembled products. Finally, there is a new trend in complex simulations to reduce computation time using fuzzy sets and fuzzy numbers (Arakawa et al. 1998; Varghese et al. 1996).

Figure 5 shows the wide range of practices. Ideally, modeling is used throughout the design process; however, less than half of commercial projects systematically model variation. In aerospace, modeling is used less frequently. Modeling includes a range of practices from RSS and tolerance chain analysis to Monte Carlo simulation using Crystal Ball™ to complex software such as VSA. Barriers to effective variation modeling include the limited modeling techniques available in the early design stages and the resources required to use existing tools. In addition, good data about manufacturing capability is also required (Section 5.2). Without process capability data, variation modeling can only be used to identify product features that are generically sensitive to variation.

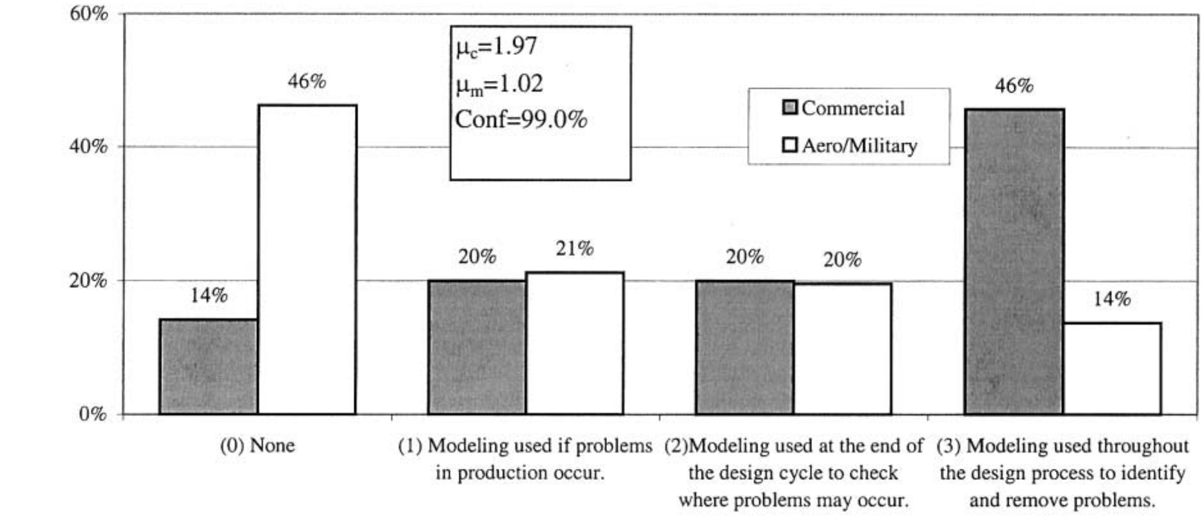

Fig. 5. Variation modeling.

5.2. Capability Feedback

Capability feedback uses process variation data collected during production to help design new products. Ideally, manufacturing groups measure and collect data about current processes and design uses this data to specify more realistic tolerances and to more accurately predict final product quality. Many companies have developed process capability databases (Lucca et al. 1995; Naish 1996; Tata and Thornton 1999); however, only a few academic references are concerned with process capability databases.

Campbell and Bernie (1996) outline requirements for a rapid prototyping database that includes feasible features and tolerances. Perzyk and Meftah (1998) describe a process selection system that includes general data on process capabilities and expected variation. In addition, several articles describe methods for predicting process capability using process models (Frey et al. 1998; Soyucayli and Otto 1998).

Many companies have process capability information systems but find these systems challenging to use in the design process (Tata and Thornton 1999). Consequently, companies (both commercial and aero/military) are not systematically using process capability data (Fig. 6) during their design process. The VRM survey has since been followed up with a detailed survey on process capability databases in industry (Tata and Thornton 1999). The second survey findings are consistent with the first.

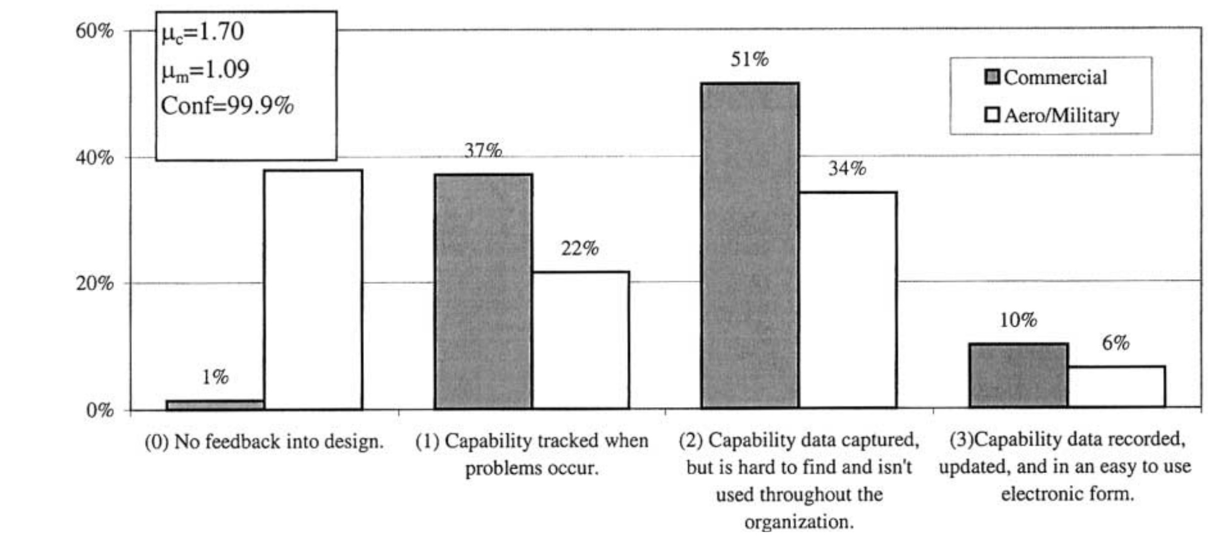

Fig. 6 Capability feedback.

5.3. Capability Uncertainty

Variation related literature typically focuses on reducing a product's sensitivity to variation (Section 6.2). However, in many cases, it is necessary to obtain better quality through processes that are more expensive, process adjustments, or higher-precision parts. Decisions to purchase extra precision are made by comparing increased unit cost against increased customer satisfaction (Lundvall and Juran 1951). However, these comparisons require accurate information about process capability; but, as pointed out above, process capability is not often used in design.

If the worst case is assumed, expensive parts, processes, and controls may be needed to offset potential quality failures. This can significantly increase unit cost. If the best case is assumed, the design team can specify lower cost parts and processes; however, there is a high probability of customer dissatisfaction. Ideally, uncertainty about process capability should be quantified and considered when selecting a quality strategy. However, current practice is not ideal.

There is virtually no literature on process capability uncertainty. Maggio (1996) describes how inexact information about Space Shuttle failure probabilities are used to bound their probabilistic risk assessment. In addition, two papers have been written by the lead author that propose methods for modeling uncertainty (Thornton 1998a; Thornton 1999). A few research papers address the use of uncertain information in design. Kim et al. (1995) quantify imprecision by propagating intervals through a constraint set. Otto and Antonsson (1995) propose mathematics to propagate imprecise constraints in a design search.

Uncertainty is not managed well in industry (Fig. 7). On average, uncertainty is acknowledged but not tracked or measured. The lack of tools and methods to quantify and manage uncertainty is an important contributor to this problem.

5.4. Summary

On average, commercial companies semi-proactively assess variation risk: modeling is used late in the design cycle, capability data is used but is hard to find, and uncertainty is acknowledged by not formally measured. Aerospace/military organizations reactively assess variation risk. Three tools would improve risk assessment maturity: tools to model variation and prioritize risk early in the design process, tools to communicate process capability, and tools to model uncertainty about process capability.

6. Risk Mitigation

Once high-risk areas are identified, the product development organization should systematically mitigate risk through design changes or production improvements. In either case, the development team should understand the cost and benefit for each option before selecting a mitigation strategy.

6.1. Cost/Benefit Trade-offs

When selecting the most appropriate mitigation strategy, it is necessary to be able to evaluate the cost and benefit of all options. Ideally, these

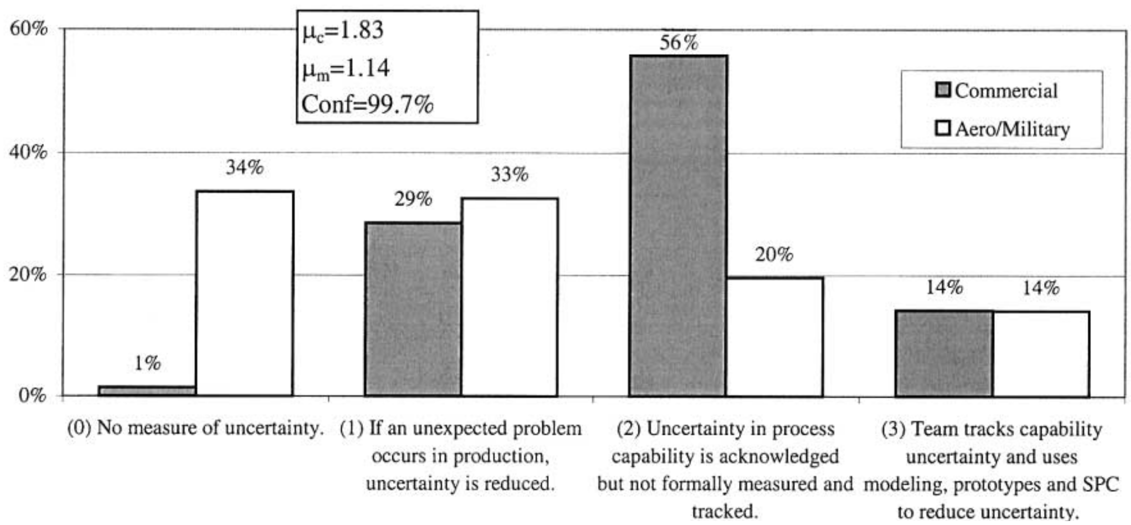

Fig. 7. Capability uncertainty.

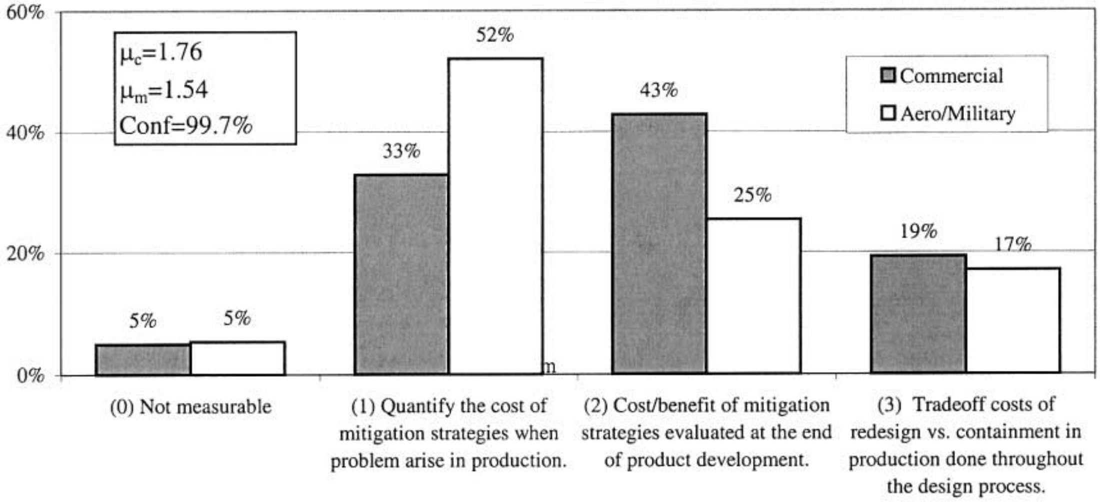

Fig. 8. Cost/benefit trade-off.

evaluations should be made throughout the design process. However, it is, at present, difficult to model these costs (Dale et al. 1998). Cost models methods range from general approaches (Taguchi 1993) to specific ones (Bowman 1994). Lundvall and Juran (1951) were the first to balance quality costs against improvement costs. In their model, cost is minimized when investment in prevention and appraisal plus failure costs is minimized. Others argue that quality cost minimization does not occur before 100% conformance is achieved (Deming 1986). The authors of this paper have written several papers on modeling the cost and benefit of mitigation strategies including variation reduction (Thornton 1998b) and inspection plans (Chen and Thornton 1999).

Companies typically estimate ROI for large initiatives (e.g. new capital equipment acquisition and major design changes); but these projects typically run over budget and schedule. In addition, while analyses are used to evaluate resource intensive changes, assessments are not systematically made throughout the design process. The extent to which companies predict cost/benefit tradeoffs for mitigation strategies is shown in Fig. 8.

6.2. Robust Design

Robust design methodologies are used to design products that are insensitive to variation. Robust design can be achieved through robust concept selection, design of experiments, and parameter design (Taguchi and Clausing 1990). Robust design can be applied proactively or reactively. Proactively, the methodology is used during design to minimize a product-KC's sensitivity to manufacturing variation. Reactively, robust design methods are used to make design changes when a design has unacceptable quality problems in production.

There is a significant set of literature on methods for and application examples of robust design[7]. There is also literature on robust design for multiple attribute problems (Iyer and Krishnamurty 1998; Pignatiello 1993; Song 1995). Different methods to optimize robustness include response surface approaches (Chen et al. 1998) and probabilistic modeling (Eggert and Mayne 1993). In addition, there is literature on robust concept selection (Andersson 1996).

While robust design is taught to most engineers, methods are still not systematically applied. As can be seen from Fig. 9, about one third of commercial companies use proactive robust design techniques. The predominance of reactive applications of robust design is due to several factors. Although many engineers are taught robust design, we often hear 'I've been trained but the example in the course had nothing to do with the products I design'. In addition, robust design is time consuming and may be sidelined when schedule and resource pressures increase. Finally, decisions are often postponed as the uncertainty about the product and the process capability makes analysis results ambiguous.

Once in production, schedule pressures reduce, process capability data becomes available and there is a product on which to experiment. In addition,

[7] Andersson 1996; Chen *et al.* 1996a; Chen *et al.* 1996b; Dunsmore *et al.* 1997; Fowlkes and Creveling 1995; Kazmer, Barkan et al. 1996; Parkinson *et al.* 1993; Phadke 1989; Taguchi 1993; Zhang and Wang 1998)

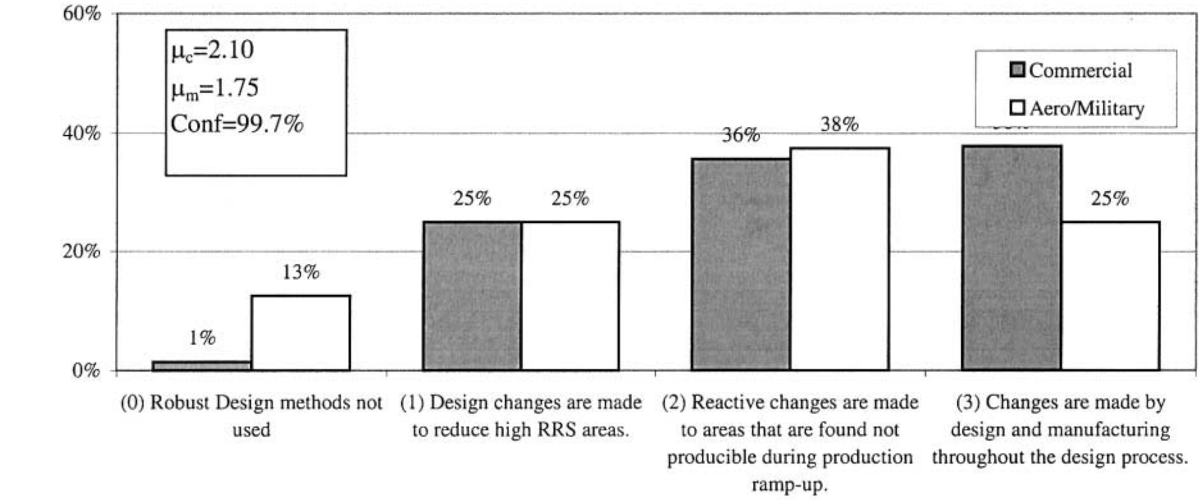

Fig. 9. Robust design.

product teams shift their focus from schedule pressures to quality pressures. These issues often induce designers to delay applying robust design until late in the design process.

6.3. Manufacturing Quality Plans

Manufacturing quality plans are the tools and methods used to improve product quality during production. A variety of standard industry quality systems have been developed including ISO 9000, QS 9000, Advanced Product Quality Planning & Control Plan (Thisse 1998), Six Sigma, and Boeing's Advanced Quality System. These systems are based on several common basic principles: teams must baseline and document their processes; teams should work together to improve detection and prevent errors; and statistical process control should be used to ensure process stability. When variation is still too high, companies should inspect to ensure quality products.

- **SPC.** Statistical Process Control (SPC) is used to track processes to ensure they don't degrade or go out of control (Montgomery 1996). The companies we interviewed all used SPC but all felt their application was not effective: they failed to react to data and had difficulty determining what to measure. This is consistent with Hoyer and Ellis' (1996) and Dale et al.'s (1998) observations.
- **Continual Improvement**. Continual improvement is the process of reducing production variation throughout the product life. Process improvement can be achieved through DOE, root cause analysis, and total production maintenance. For each, processes must be baselined, control parameters identified, control parameters adjusted, and processes monitored. These stages all require significant engineering resources. However, the results can have dramatic impacts. For example, Intel's success relies on aggressively increasing yields (DiCarlo 1998); this provides them a significant edge over their competitor, Advanced Micro Devices (AMD), who continually struggle to increase their yields (Haber 1998).
- **Inspection.** Inspection checks product acceptability and either scraps or reworks the part if it fails inspection. Early papers focused on the effect of inspection error on quality control (Mei et al. 1975; Menzefricke 1984). Other papers focus on optimization of single inspection criteria to minimize cost (Bisgaard et al. 1984; Carlsson 1989; Chen and Chung 1996; Hunter and Kartha 1977; Tang and Lo 1993), allocation of inspection in multi-product serial production systems (Chakravarty and Shtub 1987; Elmaghraby 1986; Viswanadham et al. 1996), and inspection of parts with multiple characteristics (Greenshtein and Rabinowitz 1997; Rabinowitz and Emmons 1997).

In most cases, design of manufacturing quality plans is delayed until the end of product development (Fig. 10) and is used to contain problems. Functional separation between the product designers and inspection and quality functions inhibits the achievement of a fully proactive practice. To improve this practice, several methods need to be developed. First, inspection and quality control functions should be involved early in product design. Secondly, tools to quantify the cost and benefit of quality plans need to be developed.

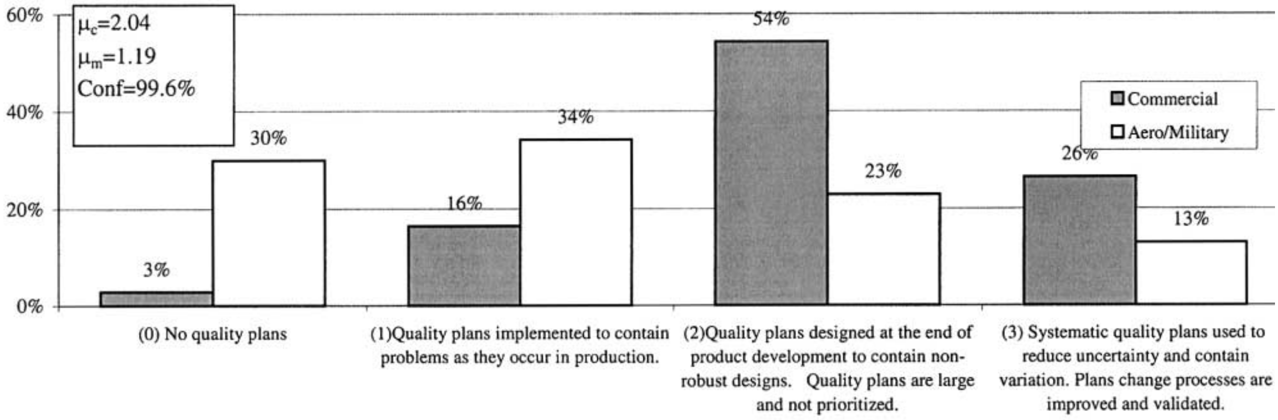

Fig. 10. Manufacturing quality plans.

6.4. Summary

On average, companies evaluate mitigation strategies late in design; they qualitatively prioritize problems; and they qualitatively calculate the cost and benefit of mitigation strategies. To solve these problems, quantitative methods to evaluate the cost and benefit of mitigation strategies need to be developed. In addition, tools to improve robustness early in design and methods to help prioritize SPC and process improvements need to be developed.

7. Practices Supporting all VRM Stages

Several practices do not directly relate to risk identification, assessment, or mitigation but support all three. These include documentation, management support, and supplier relations.

7.1. Documentation

Information relating to the variation risk management process should be available throughout the product development process and to all functional groups. Information documented during VRM typically includes the KC flowdowns, variation models, expected variations, and predicted Cpks. Because it is impossible to verbally communicate all information, documentation is needed to record and communicate information about KC flowdowns, costs, variation, quality and prioritization. While there is a significantly body of literature on product data management and design records, there is no literature that specifically addresses documenting variation information.

Variation related documentation is often informally captured in design notebooks or spreadsheets. While information contained in these locations can be

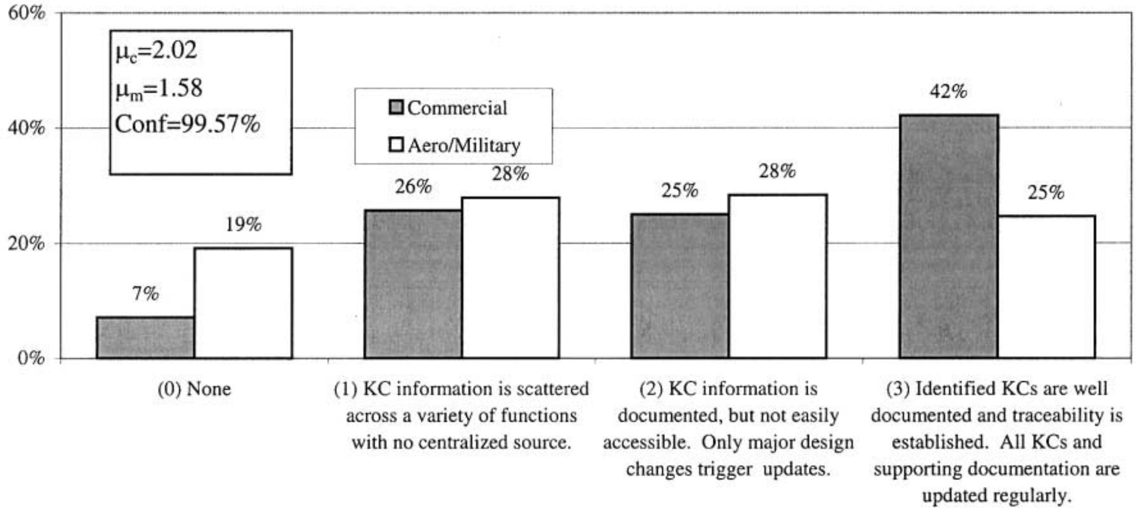

Fig. 11. Documentation.

extensive and rich, information is not available to the rest of the design team and is often lost. In many companies, drawings or quality documents are used to document KCs. In addition, several companies use an Integrated Product and Process Data Sheet. These sheets contain all cross-functional information in a single document including parts, assembly, tooling, and measurement information for each subsystem.

Many companies have developed databases to capture the flowdown and data about expected process capability, tolerances, and risks. However, current KC databases have several shortcomings. First, databases are not integrated with other information systems. Second, databases are data repositories and do not have analytic or computational capabilities. Third, data is in tabular form and it can be difficult to traverse the database to develop a system view of variation risk. Fourth, databases are not used by the entire organization and are often reinvented for each project. Because of these factors, the average maturity is level two for commercial and between one and two for aero/military (Fig. 11).

7.2. Management Support

For product development to succeed there must be active management support and leadership (Wheelwright and Clark 1995). Support typically takes the form of leadership, resources, time, incentive structures, staff training, and support systems. Management support is especially important in TQM efforts (Quinn 1995). For example, one criteria for winning the Baldridge Award for Quality is leadership 'creating and sustaining values, company action, performance expectations, customer focus, and a leadership system that promotes performance excellence' (Brown 1997).

The need for management support is especially important in Variation Risk Management (Snee 1998). Management's role can include defining strategies, communicating goals, providing resources, and rewarding good VRM practice. Management support for VRM is especially important as VRM benefits functions other than the group doing the work. VRM can increase the product development time but reduces rework in production.

While management wants to control variation, most companies do not effectively support VRM (Fig. 12). On average, companies provide resources for VRM but when crises occur, those resources are often diverted. In aero/military companies, VRM ideas are 'encouraged' but only limited resources are allocated for their execution.

7.3. Supplier Relationships

Ideally, suppliers should be brought in to evaluate producability early in the design process. In addition, supplier capability should be used to design parts that conform to supplier capability and minimize overall costs. The literature on suppliers can be broken into three groups: literature on early supplier involvement, literature on economics of supplier relations, and literature on supplier qualifications.

Most literature on product development promotes using a small supplier base, strong relations with suppliers, (Deming 1986) and early supplier involvement (Bidault et al. 1998; Dowlatshahi 1997; Hartley et al. 1997). Japanese companies' close relationships

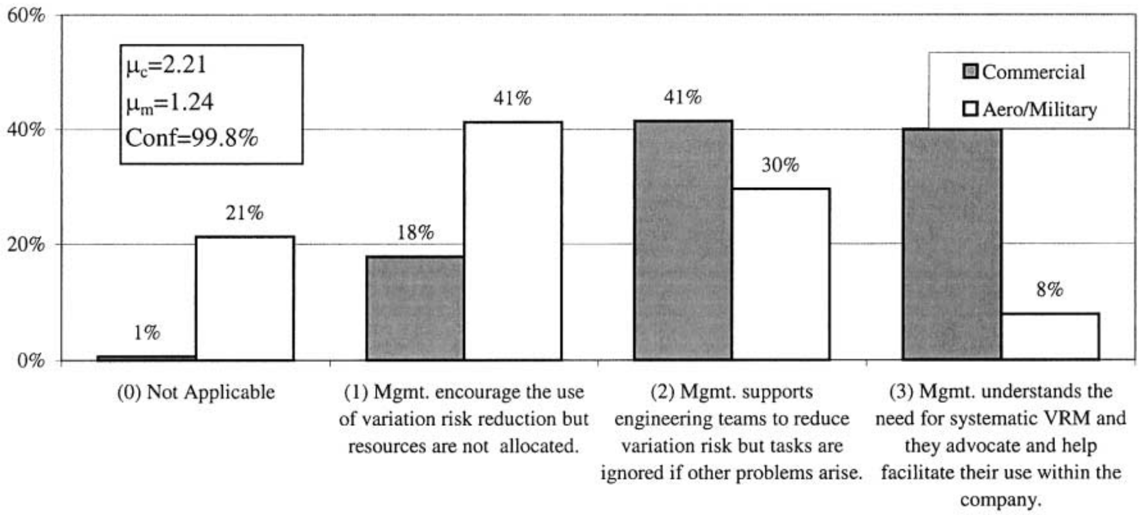

Fig. 12. Management support.

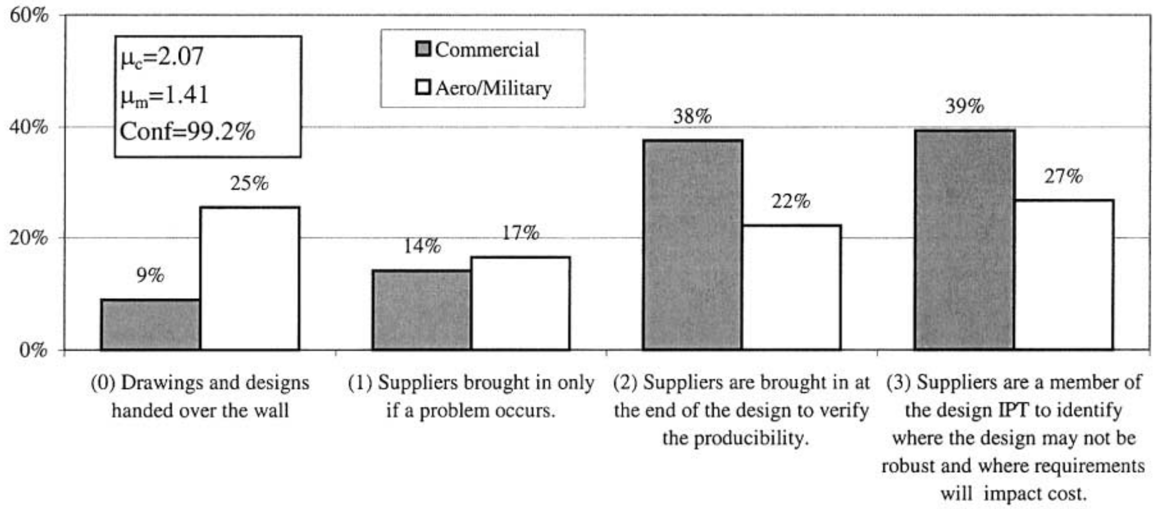

Fig. 13. Supplier relations.

with their suppliers are generally seen as an important factor in their successful product development processes (Clark and Fujimoto 1991; Womack et al. 1991).

Many articles describe buyer-supplier relationship models. These range from the economics of quality verification schemes (Lewis and Sappington 1991) to cost setting and contracting with uncertain information (Baron and Besanko 1987). In addition, there is also literature on supplier qualification processes such as Boeing's *Advanced Quality System* (Flint 1993), and Ford, GM and Chrysler's jointly developed QS-9000 (Lovitt 1996). However, these systems are focused primarily on process validation and control, rather than on product design. Figure 13 shows that a large percentage of suppliers are being brought in at the end of design rather than being involved proactively during product design. First, management does not encourage interaction with suppliers. Second, the author has repeatedly observed suppliers who are unwilling to share process capability and cost data with customers (Tata and Thornton 1999).

7.4. Summary

The supporting methods are also at level two maturity. Documentation, which is required to enable communication between functional groups, is generated but is not accessible or updated. Management wants their teams to use VRM but will often not enforce the application or withdraw resources when schedule and resource pressures increase. Finally, suppliers are not integrated into the design process but are most often brought in at the end of design to verify producability.

8. Practices Not Reviewed

Due to space constraints, the following practices were not reviewed: tolerancing, definition and methods, validation, prioritization, integrated product teams, incentive structures, training, objectives, new technology, and reuse. In all cases, commercial companies averaged a level-two maturity and the aero/military averaged between a level-one and a level-two. Companies rarely reuse variation data, new technology is not validated before it is launched, KCs aren't validated using a rigorous system, and teams have their own standard definitions but there is often disagreement among divisions about the correct definition. Further information about these practices and the industry survey can be found in Ertan (1998).

9. Conclusions

In conclusion, US industry understands the need for VRM[8]. However, despite this fact, the industries we surveyed are not implementing best practices throughout their organization. It was shown that the industries interviewed typically apply VRM practices late in the design process when the product is about to be transitioned into manufacturing. In variation

[8]This study was limited to US practices. However, the same problems and methods apply to international organizations.

management practices, aero/military organizations were significantly worse than their commercial counterparts. The difference between commercial and aero companies is a function of several issues. Aerospace/military companies typically have fewer and longer design cycles and therefore, fewer learning cycles. Aero/military manufacturing companies have also historically not been required to reduce unit costs and used rework and inspection as a way to control quality. The companies interviewed for this paper were representative of large Fortune-500 type companies. Practices used by smaller companies are similar, but the authors have observed that variation methods receive less emphasis in their design processes. The differences may be a function of many variables and this issue will be the subject for further research.

The result of this analysis is a list of areas requiring research and tool development. At the organizational and management level, VRM should be better integrated into the design process. Because there is little management support and incentives to systematically implement VRM, attention to variation is often delayed. However, increasing resources, adding VRM to the design process, and setting incentives will not solve the problem alone. Better low cost, systematic, and quantitative methods are needed in all stages of variation risk management. There is a large body of literature on complex robust analysis tools. However these tools are not being routinely used in industry because they are too complex and the data needed to populate the analyses is not available. The following list summaries the barriers and needs identified in this paper (references are given to ongoing work by the authors' research group):

- Methods to set customer requirement latitudes and flow customer requirements through the product.
- Tools that enable variation assessment early in the product development process (Thornton 1999) and to create low-cost models capable of handling complex models
- Information systems to help predict, record, and retrieve process capability and process capability uncertainty (Tata and Thornton 1999).
- Tools to quantify the impact of process capability uncertainty on yield and Cpk predictions (Thornton 1998a; Thornton 1999).
- Better methods to quantify the cost and benefit of mitigation strategies (Chen and Thornton 1999; Thornton 1998b) to both select mitigation strategies and optimally implement the selected strategy.
- Better documentation methods that enable design teams to develop a 'system view' of variation (Thornton 1999) capable of handling the complex flowdowns that typify manufactured products.

In summary, effective VRM is critical to industries' competitiveness. However, many problems prevent industry from implementing systematic and efficient VRM processes. Many of these problems are due to a lack of quantitative models that enable a design team to make quick and accurate decisions about the best use of limited variation risk management resources.

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