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DEPARTMENT OF DEFENSE HANDBOOK

MANUFACTURING MANAGEMENT PROGRAM GUIDE

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FOREWORD

1. This handbook is approved for use by all Departments and Agencies of the Department of Defense (DoD). The purpose of this handbook is to promote the timely development, production, modification, fielding, and sustainment of affordable and capable DoD systems by addressing manufacturing risks and issues throughout the program acquisition cycle. It is based upon practices developed by multiple, joint government/industry teams and the SAE G-23 Manufacturing Management Committee, which developed and published SAE AS6500, “Manufacturing Management Program.”
2. This handbook provides detailed guidance to DoD personnel for the application of SAE AS6500, Manufacturing Management Program, as well as guidance on implementing it in DoD contracts.
3. Comments, suggestions, or questions regarding this document should be addressed to ENGINEERING.STANDARDS@US.AF.MIL. Since contact information can change, the currency of this address can be verified by using the ASSIST Online database at https://assist.dla.mil.

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1 SCOPE

1.1 Scope

This handbook, which provides perspective and guidance for DoD implementation of an effective Manufacturing Management (MM) program, is applicable to all phases of DoD system acquisition. It describes proven manufacturing management practices that promote delivery of affordable and capable weapon systems. This handbook is for guidance only and cannot be cited as a requirement.

1.2 Purpose

The purpose of this handbook is to promote timely development, production, and fielding of affordable and capable weapon systems by addressing Manufacturing and Quality (M&Q) risks and issues throughout the program acquisition cycle. This handbook does not provide precise step-by-step processes on how to implement the requirements on DoD acquisition programs. There exist DoD and Service-level sources of information that provide that guidance.1 Instead, this document explains to DoD acquisition M&Q Subject Matter Experts (SME)2 how an effective MM Program should be implemented on DoD contracts (Guidance) and what the potential benefits and consequences might be if a program heeded (benefits) or failed to heed (consequences) the advice (Lessons Learned).

1.3 Statement of the problem

Successfully developing and deploying economically supportable weapon systems capable of meeting all functional user requirements can be an elusive goal. Over time, two common themes have emerged: (1) difficulty throughout all phases of acquisition in developing new manufacturing technologies, new weapon systems, modifications, and upgrades in a timely and affordable manner; and (2) difficulty in smoothly transitioning an acquisition program from the Engineering and Manufacturing Development (EMD) phase to the successful production and fielding of supportable systems.

1.3.1 Symptoms

The symptoms of the problem manifest during both the EMD and Production & Deployment phases of acquisition.

1.3.1.1 Symptoms during Development

During development, M&Q requirements are often not adequately identified and communicated to developers. Even when clearly identified and communicated, frequent modifications to product design specifications often ensue. Requirement fluidity impedes manufacturing maturity. Immature manufacturing processes open the door to increased process variation/poor quality, higher production costs, and schedule delays. Eventually, poor quality may lead to unexpected failure modes and numerous resultant configuration changes that challenge the support community, driving the need for larger spares inventories. For reparable items, high initial repair rates induce excessive failure analyses and corrective actions, requiring more complex configuration tracking systems and numerous technical order changes.

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[1] For example, the DoD Manufacturing and Quality Book of Knowledge, available at https://ac.cto.mil/maq/, contains step-by-step instructions "*for completing M&Q activities across the DoD system acquisition life cycle*".

[2] This paragraph introduces a short-hand, catch-all term used herein to include, for example, a variety of degrees/professions that make up the intended audience of this document, including, but not limited to, Industrial & Systems Engineers (increasingly called Integrated Systems Engineers), Manufacturing Engineers, Quality Engineers, and Industrial Specialists.

1.3.1.2 Symptoms during Production & Deployment

Upon completion of EMD, many modern acquisition programs continue to experience difficulties during the transition to, and subsequent execution of, Production & Deployment. Symptoms identified during development persist and expand, such as:

- cost inflation
- poor manufacturing quality
- low process yields
- inability to support production rates while continuing to rely on processes used to produce development units
- schedule delays incurred while true production-rate-capable processes are being matured

Ultimately, this chain of interconnected issues results in increased costs and challenges the warfighters to maintain optimal operational capability.

1.3.2 Root causes

The root causes of the symptoms described in paragraph 1.3.1 can be traced to:

- ineffective planning for the development and maturation of production processes during pre-production acquisition phases concurrent with product development.
- incomplete understanding of the relationship between key design requirements, the processes needed to support them, and the impact of this relationship on product performance/supportability, cost, and schedule.
- ineffective risk assessment, mitigation, and monitoring activities supporting critical process development, to include ineffective conduct of production readiness reviews.
- a lack of clear and concise vertical and horizontal communication links throughout the supply chain.

Unfortunately, these risk factors manifest themselves throughout every program lifecycle, as shown in Table 1: Examples of phase-specific risk factors.

Table 1: Examples of phase-specific risk factors

Program Phase	Risk Factors
Pre-EMD Inadequate planning to address production risk	Inadequate understanding of existing process capabilities (process characterization) Limited source selection criteria related to process capability No long-range production investment strategy as part of the overall acquisition strategy Unstable requirements: unreasonable expectations regarding requirements and demonstrated process capabilities Lack of programmatic focus on addressing process development needs during product development

Table 2: Examples of phase-specific risk factors – Continued

Program Phase	Risk Factors
EMD Insufficient attention to process capability development	Insufficient or untimely consideration of producibility analyses Product design instability resulting from an emphasis on meeting performance requirements without consideration of producibility Insufficient identification of key product characteristics and key manufacturing processes Late initiation of production planning and risk mitigation efforts Lack of exit criteria for key processes and a lack of process related milestones
Production Ineffective process control	Undefined process control requirements for key characteristics and critical manufacturing processes Non-existent or ineffective process improvement efforts Lack of hard cost control requirements; no incentives to control / reduce life cycle cost

1.4 Success criteria

To battle these root causes and to achieve MM Program objectives, the strategies and associated best practices identified in Table 3 should be pursued.

Table 3: MM Program best practices

Strategy	Best Practices
Balance product requirements with process capability considerations	Balance investments in both product and process development during pre-production program phases Consider process capability in technology development and insertion efforts Incorporate evaluation criteria for production process capability during source selection with firm requirements for process development, process validation, process control, and production cost estimation Implement a well-defined production investment strategy as part of the overall acquisition strategy
Pursue process capability development concurrently with product capability development	Identify exit criteria for all key events and milestones appropriate to developing, establishing, and validating required process capabilities Stabilize the product design early in the development program through balanced trades between performance, cost, and schedule, with attention to producibility and supportability Consider production-related issues such as Special Tooling (ST), Special Test Equipment (STE), and Support Equipment (SE) design and fabrication; and use of actual production processes to fabricate, assemble, and test prototype equipment to prove the manufacturing process Use modeling and simulation of the design, production, and support environments
Establish a product and process development environment that implements the practices of key characteristic identification, process control, variability reduction, and defect prevention	Require flow down practices which identify key product characteristics, key production processes, and key process parameters throughout the supply chain Define process control practices identified in the build-to data package Implement efficient variability reduction programs which improve dimensional control, yield higher product/process quality and reliability, and create an environment of preventive rather than corrective action

The best practices presented in Table 3 drove the specific requirements of an effective MM Program described herein; motivation for and elaboration of those requirements are the focus of the remainder of this handbook.

1.5 Benefits

This handbook provides guidance that ensures contractual language is placed in defense contracts that challenge the defense industry to follow their own manufacturing management program standards/best practices. Some of the practices will require an up-front investment in early development, with returns not realized until later in development and production (see paragraph 4.4.1). However, the potential returns on investment can include:

- shorter development schedules and reduced cycle times
- more robust product designs
- easier transition of designs to production
- more effective risk management
- improved supplier product integration
- better product quality and reliability

Achieving the full range of benefits available from the practices may therefore require cultural changes on the part of some, from end-users through lower-tier suppliers.

2 APPLICABLE DOCUMENTS

The documents listed below are not necessarily all of the documents referenced herein but are those needed to understand the information provided by this handbook.

2.1 General

The following Government documents, drawings, and publications form a part of this document to the extent specified herein.

2.2 Government documents

2.2.1 Specifications, standards, and handbooks

The following specifications, standards, and handbooks form a part of this document to the extent specified herein.

MIL-HDBK-516 — *Airworthiness Certification Criteria*

(Copies of this document are available online at https://assist.dla.mil.)

MIL-HDBK-539 — *Digital Engineering and Modeling Practices*

(Copies of this document are available online at https://assist.dla.mil.)

2.2.2 Other Government documents, drawings, and publications.

DEPARTMENT OF DEFENSE

DOD-STD-2101 — *Classification of Characteristics*

(Copies of this document are available online at https://assist.dla.mil.)

DoD Manufacturing Technology Program — *Manufacturing Readiness Level (MRL) Deskbook*

(Copies of this document are available online at https://www.dodmrl.com/.)

DoD Office of the Deputy Assistant Secretary of Defense for Systems Engineering — *DoD Risk, Issue, and Opportunity (RIO) Management Guide for Defense Acquisition Programs*

(Copies of this document are available online at https://www.cto.mil/wp-content/uploads/2024/05/RIO-2023-2-2.pdf)

DoD Office of the Under Secretary of Defense (OUSD) for Research and Engineering (R&E) — *Systems Engineering Guidebook*

(Copies of this document are available online at https://ac.cto.mil/wp-content/uploads/2022/02/Systems-Eng-Guidebook_Feb2022-Cleared-slp.pdf

DoD Office of the Under Secretary of Defense for Research and Engineering — *DoD Producibility and Manufacturing Engineering Guide*

(Copies of this document are available online at https://www.cto.mil/wp-content/uploads/2024/06/DoD-Producibility-and-Manufacturability-2024.pdf

Joint Aeronautical Commander's Group — *Aviation Critical Safety Item Management Handbook*

(Copies of this document are available online at https://dap.dau.mil/Pages/Default.aspx.)

UNITED STATES NAVY

NAVSEA INSTRUCTION 9078.1 — *Naval Ships Critical Safety Items Program, Non-Nuclear*

(Copies of this document are available online at https://www.navsea.navy.mil/Portals/103/Documents/NAVINST/09078-001.pdf.)

UNITED STATES ARMY

AR 770-3 — *Army Regulation: Type Classification and Materiel Release*

(Copies of this document are available online at https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN33712-AR_770-3-001-WEB-3.pdf.)

2.3 Non-Government documents

The following documents form a part of this document to the extent specified herein.

Automotive Industry Action Group (AIAG) MSA Reference Manual

IEEE 15288.2 — *IEEE Standard for Technical Reviews and Audits on Defense Programs*

(Available at https://standards.ieee.org/index.html.)

ISO 9001 — *Quality management systems – Requirements*

(Available at https://www.iso.org/iso/home.htm.)

SAE AS5553 — *Fraudulent/Counterfeit Electronic Parts; Avoidance, Detection, Mitigation, and Disposition*

SAE AS6500 — *Manufacturing Management Program*

SAE AS9100 — *Quality Management Systems – Requirements for Aviation, Space and Defense Organizations*

SAE AS9102 — *Aerospace First Article Inspection Requirement*

SAE AS9103 — *Aerospace Series – Quality Management Systems – Variation Management of Key Characteristics*

SAE AS9017 — *Control of Aviation Critical Safety Items*

SAE AS9110 — *Quality Management Systems – Requirements for Aviation Maintenance Organizations*

SAE AS9145 — *Requirements for Advanced Product Quality Planning and Production Part Approval Process*

SAE AS13003 — *Measurement Systems Analysis Requirements for the Aero Engine Supply Chain*

SAE J1739 — *Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing, Assembly Processes (Process FMEA), and Effects Analysis for Machinery (Machinery FMEA)*

(SAE documents are available at https://www.sae.org/.)

3 DEFINITIONS

This handbook is intended to be used in conjunction with SAE AS6500. Refer to SAE AS6500 for manufacturing-related definitions.

4 MANUFACTURING MANAGEMENT PROGRAM FUNDAMENTALS

4.1 The Benefits of an effective MM Program

Prior to a production decision, an effective MM Program ensures capable manufacturing processes are developed concurrent with product design activities. After product/process development has been concluded and the production decision has been made, an effective MM Program ensures capable, efficient processes produce quality product. The following paragraphs discuss MM Program requirements in relation to Systems Engineering Process, the relationship between MM Program requirements and Manufacturing Readiness Level threads, and acquisition strategies for implementing MM Program requirements on contracts. A more thorough treatment of the benefits of an effective MM Program is provided in Appendix A.

4.2 Manufacturing Management as part of the Systems Engineering Process

M&Q SMEs should be key members of the development team, participating actively during each phase of an acquisition program, integrating M&Q considerations into the earliest phases of the product development life cycle. Another way of saying this is that M&Q SMEs should be active participants in each step of the Systems Engineering (SE) Process (Table 4: M&Q participation in SE).

Table 4: M&Q participation in SE

SE Activity	M&Q SME Participation
Planning	M&Q should ensure the Systems Engineering Plan (SEP) includes discussions of manufacturing risks, staffing, metrics, and tools. The SEP should include manufacturing assessments utilizing the Manufacturing Readiness Level (MRL) Process. The SEP should also describe how available manufacturing capabilities will influence product design decisions and how these trade-offs will be addressed in technical reviews and audits. M&Q SMEs should also include significant manufacturing events and reviews in the Integrated Master Plan (IMP).
Development	M&Q should ensure producibility (including quality verifications) are addressed as design considerations. They should ensure contractor manufacturing engineers are providing process capability data to designers and evaluating proposed design requirements (for example, tolerances) against available process capabilities. As a best practice, manufacturing representatives should coordinate on product designs.
Verification/Validation	M&Q should participate in product verification and validation process. The Verification process provides the evidence that the system or system element performs its intended functions and meets all performance requirements listed in the system performance specification and functional and allocated baselines. Verification answers the question, “Did you build the system correctly?”[3] The Validation process provides the objective evidence that the system capability complies with stakeholder performance requirements, achieving its use in its intended operational environment. Validation answers the question, “Is it the right solution to the problem?”[4]

[3] Systems Engineering Guidebook, 4.2.6, Feb 2022
[4] Systems Engineering Guidebook, 4.2.7, Feb 2022

Table 5: M&Q participation in SE – Continued

SE Activity	M&Q SME Participation
Risk Management	M&Q should ensure the program's risk management process identifies and addresses manufacturing risks (for example, those identified during MRL assessments). M&Q should participate in Systems Engineering technical reviews. Minimally, manufacturing readiness levels should be assessed commensurate with technology readiness levels during design reviews (for example, Preliminary Design Review (PDR) and Critical Design Review (CDR), with heavy focus on producibility during the development phase). As the SE process culminates in a producible design, manufacturing readiness becomes the primary focus of Production Readiness Reviews[5].
Qualification, Materiel Release, & Certification	M&Q should participate in the qualification, materiel release, and certification processes. MIL-HDBK-516, "Airworthiness Certification Criteria", specifies manufacturing and quality criteria that must be met to secure airworthiness certification. Specific M&Q airworthiness criteria are presented in MIL-HDBK-516 paragraph 4.4. MM Program best practices, as expounded herein, are intended to satisfy the M&Q airworthiness criteria; therefore, when MM Program requirements are on contract and implemented effectively, manufacturing and quality airworthiness criteria should be satisfied[6]. For non-aerospace materiel, Department of the Army Regulation 770-3, "*Type Classification and Material Release*", describes a type classification process that ensures materiel, including commercially available materiel, is acceptable for Army use prior to procurement. It also describes a materiel release process that ensures procured materiel is safe, suitable, and supportable.

4.3 MM Program Requirements vs Manufacturing Readiness Level Threads

MRLs are used to assess manufacturing readiness risk as a program moves through the product and process development phase into production. MRLs provide specific expectations of evolving manufacturing maturity, thereby establishing a common baseline for manufacturing risk identification and mitigation efforts. Table 6: MRL threads to MM Program requirements cross-reference matches MM Program requirements to MRL threads. MM Program requirements, effectively implemented, make it reasonable to expect that associated MRL threads will reach target level at each incremental systems engineering review (for example, PDR, CDR, PRR).

Table 6: MRL threads to MM Program requirements cross-reference

MRL Thread	Para #	Requirement
Technology & Industrial Base	5.4.2	Materials Management
	5.4.3	Manufacturing Technology Development
Design	5.2.1	Producibility Analysis
	5.2.2	Key and Critical Characteristics
	0	Process Failure Mode and Effects Analysis (PFMEA)
Cost & Funding	5.4.4	Cost

[5] Further guidance on formal technical reviews is presented in IEEE 15288.2.
[6] It is ultimately the responsibility of the program's Chief Engineer to verify airworthiness criteria have been met.

Table 7: MRL threads to MM Program requirements cross-reference – Continued

MRL Thread	Para #	Requirement
Materials	5.4.2	Materials Management
	5.5.8	Supplier Management
Process Capability & Control	5.4.5	Manufacturing Modeling and Simulation
	5.5.3	Continuous Improvement
	5.5.4	Variability Reduction
	5.5.5	Process Capabilities
Quality Management	5.3	Manufacturing Risk Identification
	5.5.2	Manufacturing Surveillance
	5.5.3	Continuous Improvement
	5.5.7	First Article Inspections (FAIs)/First Article Tests (FATs)
	5.5.8	Supplier Management
	5.5.9	Supplier Quality
Manufacturing Workforce	5.4.7	Manufacturing Workforce
Facilities	0	Tooling/Test Equipment/Facilities
Manufacturing Management	5.4.6	Manufacturing System Verification
	0	Production Scheduling and Control
	5.5.2	Manufacturing Surveillance
	5.5.4	Variability Reduction

4.4 Acquisition Strategy Considerations

DoD acquisition and sustainment community M&Q SMEs need to be cognizant of not only the technical considerations which predominate the discussion of MM Program requirements in Section 5, but also their business and contracting impacts. Therefore, before launching into the technical details of each MM Program best practice, the following subsections address considerations regarding, and implications of, imposing MM Program requirements on a contract, to include those involving funding profiles, Requests for Proposal (RFP) language, and contract statements of work.

4.4.1 Funding implications

Funding profiles, managed properly, will motivate doing the right task at the right time. One of the most important business issues related to the implementation of MM Program requirements and the guidance of this handbook is *how* and *when* to properly fund programs to take advantage of MM Program best practices. MM Programs require early involvement of the manufacturing engineering discipline in the design process to prove manufacturing processes prior to the start of production (Figure 1).

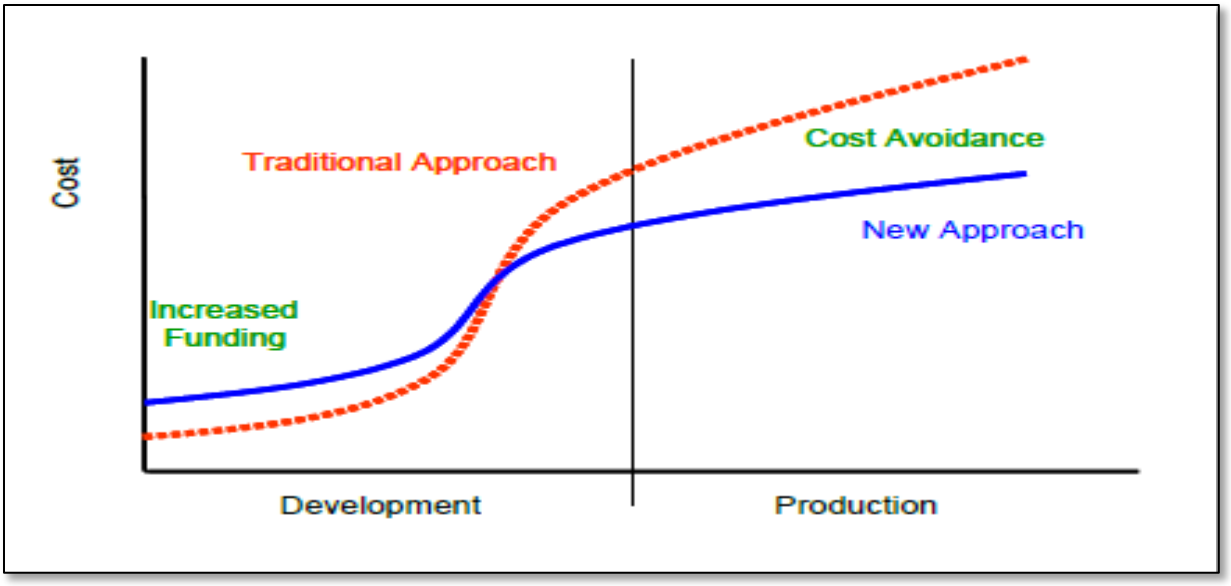

Figure 1: MIL-HDBK-896B vs traditional program funding profiles

4.4.1.1 Development phase cost estimating implications

Development phase cost estimating must now consider the effects of additional investment in MM Program activities. This handbook promotes several acquisition approaches that require a greater investment of effort up-front, such as producibility studies, assessments of manufacturing risks, earlier manufacturing process maturation, and modeling and simulation. Engineering and tooling hours, for example, may shift significantly earlier as manufacturing analysis efforts are integrated into product design activities sooner.

4.4.1.2 Production phase cost estimating implications

Production phase cost estimating must now anticipate the return on investing in MM Program activities. Early investment in design producibility and manufacturing process planning should yield significant production cost savings due to, for example:

- Significant reduction in system redesigns. Traditionally, systems and the processes that produce them have been plagued by changes made late in development, even into early production; first unit costs have been impacted due in part to the significant amount of rework needed to incorporate design changes. MM Program initiatives should reduce redesign and tooling rework efforts.
- Better integration of the design, quality, and manufacturing processes. This should yield improved production efficiency (for example, reduced build times; reduced scrap, rework, and repair). Modeling and Simulation (M&S) tools (discussed in Section 0) are a significant enabler of improved production process efficiency through reduced build times. M&S may permit identification and resolution of production issues prior to physical fabrication and assembly of hardware. The early, most inefficiently produced units of production are realized in a *virtual* environment; production of the first *physical* unit inherits the benefit of a head start further down the normal cost improvement curve.
- More efficient, earlier integration of suppliers and their components into the production system. This should reduce miscommunication errors and supplier engineering change requests.

4.4.1.3 Benefits of the "New Approach" funding profile

While the "New Approach" investment curve in Figure 1 remains higher than the "Traditional Approach" through much of the development phase, the benefits of the investment eventually pay off as improved producibility and better prepared production processes yield cost avoidance. For example, one specific anticipated benefit derived from making earlier investment in design producibility is that design changes will be significantly reduced, according to some estimates, by 50% or more. Anecdotal evidence in support of such cost avoidance claims is promising. One program estimated MM Program practices, appropriately funded and pursued, would have reduced tooling costs alone by 40%. Well-timed application of MM Program practices reduces design iterations in the later stages of development; this translates into lower unit production costs and ultimately, over time, into reduced overall life-cycle cost.

4.4.2 Request for Proposal Considerations

The program office may determine that an offeror's MM Program is a discriminating factor in the award of the contract. If so, Section L of the RFP, "Instructions, conditions, and notices to offerors or respondents", may require offerors to describe their manufacturing management program, for example, "*The offeror shall describe how their manufacturing management program meets the requirements of SAE AS6500*." Because onsite surveys are a proven source selection best practice, program offices may elect to include additional Section L instructions requiring offerors to support them, for example, "*The Government reserves the right to conduct an onsite survey to assess the offeror's manufacturing management program.*" RFP Section M, "Evaluation factors for award", should include a statement explaining how offeror proposals will be evaluated, for example, "*This subfactor is met when the offeror's proposal describes how their manufacturing management program meets each of the requirements of SAE AS6500.*"

4.4.2.1 Award fee inputs

The government program office may incorporate into the contract an award fee incentive tied to the effective implementation of an MM Program. The following considerations may assist in developing the award fee criteria:

- Is a manufacturing plan available? Does the plan include approaches for (1) identifying key characteristics and critical manufacturing processes, (2) performing variability reduction activities and (3) supporting manufacturing capability assessments? Does the plan describe an active, aggressive producibility program?
- Is a quality plan available? Does the plan require implementation of an effective Quality Management System focused on defect prevention?
- Is a subcontract management plan available? Does the plan clearly describe the implementation of a world-class supplier management process that ensures exceptional supplier performance? Have metrics been established at the prime contractor and with suppliers to accurately measure cost, schedule, and quality performance during development? Can the prime contractor quickly provide supplier performance insight using predictive indicators?

4.4.2.2 Award fee evolution

Once these plans have developed and are satisfactory, the Award Fee criteria should evolve to focus on evaluation of the manufacturing, quality, and supplier management metrics. Examples include satisfactory schedule performance, reductions in out-of-station work and scrap/rework/repair, and improvements in Cost of Quality, process capabilities, and supplier delivery performance. Criteria should be tailored to address program-specific circumstances, priorities, and risks.

4.4.2.3 Tailoring SAE AS6500 Requirements

SAE AS6500 requirements can be applied in full or tailored. Full conformance means that all the requirements of the standard must be satisfied; tailored compliance means that some of the requirements have been modified by mutual agreement. Evidence of compliance, whether it be to full or tailored SAE AS6500 requirements, involves an evaluation of artifacts addressing both manufacturing planning and execution. Regarding Planning, SAE AS6500 requires contractor plans, processes, and procedures to be provided for review to ensure each requirement of the standard is adequately addressed. Regarding Execution, SAE AS6500 requires the contractor to make available evidence of compliance (for example, analyses, metrics, work instructions, process controls) demonstrating the plans, processes, and procedures addressing each requirement of the standard are being implemented.

4.4.2.3.1 General Tailoring Considerations

Consider the following when tailoring SAE AS6500:

a. The program's Acquisition Strategy: Determine how the MM Program relates to the overall program strategy and requirements.

b. The expected scale of the program: Ensure MM Program requirements are appropriate to the size and scope of the program.

c. Documents referenced in SAE AS6500: If the program requires contractor compliance with any of the documents referenced in SAE AS6500, those documents must be called out separately in the contract.

d. The degree of Commercial Off-The-Shelf (COTS) content: Determine the extent to which COTS products will be used and how it impacts manufacturing requirements and planning.

e. Software: For programs that are primarily software in nature, an MM Program may not be applicable.

f. Requirements, determined by program leadership, that apply to their specific situation. Examples of typical situations include:
   1. Materiel Solutions Analysis (MSA) phase
   2. Technology Maturation and Risk Reduction (TMRR) phase
   3. EMD phase
   4. Production phase
   5. Sustainment phase (including supply support, spares, and repairs)
   6. Commercial derivative development (a commercially produced item modified for military use)
   7. Build-to-print production

4.4.2.3.2 Situational Tailoring Considerations

Table 8 details the recommended application of SAE AS6500 requirements for typical situations provides guidance for tailoring requirements of the standard based on the situation.

Table 8: Recommended application of SAE AS6500 requirements for typical situations

Para#	Requirement	MSA	TMRR	EMD	Production	Sustainment	Commercial Derivative	Build to Print
5.2	Design Analysis for Manufacturing	Y	Y	Y	Y	As needed	Y	Y
5.2.1	Producibility Analysis	Y	Y	Y	Y	As needed	Y	N
5.2.2 0	Key and Critical Characteristics Process Failure Modes Effects Analysis	N N	Y N	Y Y	Y As needed, to evaluate major design and process changes	As needed As needed	Y Y	As needed Y
5.3	Manufacturing Risk Identification	Y	Y	Y	Y	Y	Y	Y
5.3.1	Manufacturing Feasibility Assessments	Y	Y	N	N	As needed	As needed	N
5.3.2	Manufacturing Readiness Level Assessments	Y	Y	Y	Y	Y	Y	Y
0	Production Readiness Reviews	N	N	Y	Y	N	As needed	As needed
5.4	Manufacturing Planning	N	N	Y	Y	Y	Y	Y
0	Manufacturing Plan	N	N	Y	Y	Y	Y	Y
5.4.2	Materials Management	Y	Y	Y	Y	As needed	Y	As needed
5.4.3	Manufacturing Technology Development	Y	Y	As needed	As needed	As needed	As needed	N
5.4.4	Cost	Y	Y	Y	As needed	As needed	Y	As needed
5.4.5	Manufacturing Modeling and Simulation	Y	Y	Y	As needed, to evaluate major design and process changes	N	Y	N
5.4.6	Manufacturing System Verification	N	N	Y	As needed, to evaluate major design and process changes	Y	N	Y

Table 9: Recommended application of SAE AS6500 requirements for typical situations – Continued

Para#	Requirement	MSA	TMRR	EMD	Production	Sustainment	Commercial Derivative	Build to Print
5.4.7	Manufacturing Workforce	N	N	Y	Y	Y	Y	Y
0	Tooling/Test Equipment/Facilities	Y	Y	Y	Y	Y	Y	Y
0	Measurement System Analysis	N	N	Y	Y	Y	Y	Y
5.5	Manufacturing Operations Management	Y	Y	Y	Y	Y	Y	Y
0	Production Scheduling and Control	Y	Y	Y	Y	Y	Y	Y
5.5.2	Manufacturing Surveillance	Y	Y	Y	Y	Y	Y	Y
5.5.3	Continuous Improvement	N	N	Y	Y	Y	Y	Y
5.5.4	Variability Reduction	N	N	Y	Y	Y	Y	Y
5.5.5	Process Capabilities	N	N	Y	Y	Y	Y	Y
5.5.6	Production Process Verification	N	N	Y	Y	As needed	As needed	As needed
0	First Article Inspections/First Article Tests	N	N	Y	Y	As needed	As needed	As needed
5.5.8	Supplier Management	Y	Y	Y	Y	Y	Y	Y
5.5.9	Supplier Quality	N	N	Y	Y	Y	Y	Y

4.4.2.3.3 Tailoring for Maintenance, Repair, Overhaul (MRO) and depot activities

MRO and depot functions include the induction of a unit to be repaired or overhauled, a diagnostic evaluation of the unit to determine if there are issues that need to be addressed over and above (O&A) the planned work, and a measure of unit disassembly, re-manufacturing or refurbishment, re-assembly, test, and acceptance. As can be seen, MRO operations perform an assortment of processes common to production lines, except that they also incorporate diagnostic and disassembly elements. Because of the commonalities (fabrication, assembly, test, acceptance), MRO operations benefit from, and therefore require, the application of MM Program best practices. While there are similarities to original equipment production activities, there are also legitimate differences; tailoring MM Program requirements for MRO and depot activities may be necessary. Not all MRO and depot operations require design activity; therefore, the design producibility requirements may not be applicable. Furthermore, supplier management activities may be more complex than what is experienced when a single prime contractor is responsible for managing the final assembly process and the supply chain that feeds it. Depots may rely on supplied parts from all the following: prime contractors, lower tier suppliers, direct contracts with vendors, and parts purchased from separate supply chain

management organizations (for example, the Defense Logistics Agency (DLA)). Application of MM Program supplier management requirements will need to be tailored to reflect the nature of the relationship with each of the various organizations responsible for purchasing parts. When MRO activities are performed by contractors, SAE AS6500 should be imposed on the prime contractor, tailored appropriately. For organic depots that are not governed by a contract, SAE AS6500 should be cited as a requirement in the organic depot tasking statement; depot leadership should recognize the performance and competitiveness benefits of applying MM Program best practices to their organizations.

4.4.2.3.4 Tailoring for limited production quantity programs

Limited production quantity programs include, for example, those involving space vehicles (for example, launch vehicles, satellites), large ships/boats (for example, aircraft carriers, submarines), and specialized aircraft (for example, Air Force One). Even though production quantities are low, limited production programs can still benefit from MM Program requirements. In the environments many low production quantity programs inhabit (for example, space), sound manufacturing management practices become more important rather than less so; systems and their components will be required to exhibit extraordinary quality and reliability characteristics since they may not be readily accessible for repair. MM Program requirements therefore cannot be dismissed outright; they need to be analyzed and appropriately tailored to low quantity programs. Tailoring considerations include, for example:

- More emphasis on processes capable of reliably producing quality product than on efforts to optimize repetitive manufacturing cost efficiency.
- Less emphasis on M&S activities analyzing factory process capacity and throughput.
- Greater discernment in, rather than outright dismissal of, the use of process control and variability reduction activities. Even if only one end-product is produced, processes required to produce its parts may be repeated hundreds or thousands of times (for example, hole drilling), thereby presenting opportunities to benefit from statistical process control techniques.

4.4.3 Contract considerations

SAE AS6500 was written with the expectation that it would be imposed contractually[7]. While the requirements are considered industry best practices, and many manufacturers therefore elect to implement them absent a contractual requirement, a recent Independent Review Team (IRT) discovered many best practices are not implemented when the contract lacks explicit contractual manufacturing management requirements. Therefore, to ensure MM Program requirements are fully implemented by the prime contractor and key suppliers, SAE AS6500 should be explicitly cited as a contract requirement in their SOW, for example, “The contractor’s Manufacturing Management Program shall meet the requirements of SAE AS6500.”

[7] This handbook, however, serves only as a guide and should not be invoked in SOW requirements except to provide additional, non-binding guidance.

5 REQUIREMENTS

This section provides, for each MM Program requirement, brief background information, guidance, and lessons learned. Expanded background information for some of the more complex topics, presenting historical perspectives regarding the motivation for the requirement and the manufacturing issue it is intended to address, is provided in appendices. The guidance portion of each requirement describes what we, as DoD M&Q acquisition professionals, should do, and what we should expect our contractors to do in response to the requirement. The lessons learned section for each requirement shares anecdotes describing what went well when MM Program requirements were addressed properly and what went poorly when they were not. To ease cross-referencing of the SAE AS6500 requirement with the guidance contained herein, the presentation of topics in this section mirrors the SAE AS6500 paragraph structure.

5.1 Manufacturing management system

An effective MM Program specifies in formal documentation the principles, procedures, and organizational responsibilities for each MM Program requirement described in this handbook.

5.1.1 Guidance

The approach to creating and implementing an effective MM Program is no different from any other management program. A thoughtful, documented collection of artifacts describing the manner in which SAE AS6500 requirements will be tackled is required. It should describe an organized framework of principles and procedures according to which manufacturing management of the program will be accomplished. Section 0 provides additional information regarding manufacturing planning documentation.

5.1.2 Lessons Learned

Lessons learned regarding implementation of the manufacturing management system best practice are presented in Table 10:

Table 10: Manufacturing Management System Lessons Learned

#	Lesson Learned
1	A Navy program realized that small and sometimes trivial changes in the production of a proven design had subtle, unpredictable, and often significant impacts on performance. On development contracts MM Programs were implemented that required subsystem contractors to develop the production capability in conjunction with the subsystem design. The production capability effectively became part of the Technical Data Package (TDP). Both the design and the production processes were evaluated during testing. Once complete, strict controls were applied to ensure reproducibility of the design and avoid undesirable consequences of changes.

5.2 Design analysis for manufacturing

There are three best practices associated with design analysis for manufacturing: (1) Producibility Analysis, (2) Key and Critical Characteristics, and (3) Process Failure Mode and Effects Analysis (PFMEA). Each of these will be addressed in the following subparagraphs in turn.

5.2.1 Producibility analysis

An effective MM Program performs producibility analysis during product design and development. The producibility process selects candidate items, analyzes producibility drivers, conducts trade studies, objectively evaluates cost/benefits of potential producibility projects, and monitors approved producibility projects. Institutionalizing producibility analysis as part of the design trade study process supports design and development of affordable weapon systems. Design trade studies that address producibility concerns effectively balance system features

(above threshold) with program cost and schedule objectives/constraints. It is important to emphasize that producibility analysis is a design accomplishment; it is an element of the design process that cannot be introduced after the design is complete. Because producibility analysis is a design accomplishment, it should be an integral part of all design activities as they are occurring; it should be an important, persistent resident in the design alternative analysis trade space.

5.2.1.1 Guidance

A smooth transition from development to production is substantially enabled by active and effective producibility analysis accomplished during the design and development phase. Programs that do not address producibility early in product design and development often experience significant production cost increases due to poor manufacturing performance measured against the established standard amount of time to compete a task, excessive rework and repair, and disruption caused by redesign actions necessary to modify designs that are found to be unproducible.

5.2.1.1.1 Selecting producibility project candidates

Consider the following criteria when deciding where to target producibility efforts:

- assemblies with low rates of process efficiency
- assemblies that are time-consuming or difficult to assemble
- assemblies consisting of many parts
- assemblies consisting of expensive or difficult to manufacture parts
- parts and assemblies experienced excessive field failures (which could possibly be improved by a more robust design)
- production areas experiencing high cost of quality
- assemblies with a large number of shims

5.2.1.1.2 Addressing producibility challenges

The product design process should introduce manufacturing considerations into the trade space, integrating an evaluation of the production cost impact of each option. Design trade analyses should strive for robust product designs tolerant to variation in the intended manufacturing, assembly, test, and usage environments. They should be capable of identifying the design that best balances technical features with program cost and schedule constraints. Product designers should assess the producibility of as many design concepts as time and funding allows, with the level of detail and accuracy dependent on the relative contribution of each concept to achieving the production cost target or requirement. The introduction of new technology can also introduce new design challenges. Utilizing concepts unproven in a production environment may result in severe cost and schedule problems. Environmental limitations should be addressed when analyzing alternatives. The benefits of utilizing commercial parts and processes and the affordability penalties resulting from the use of non-standard parts and processes should also be evaluated and documented in design trade-off decisions. The manufacturing organization should communicate process capabilities to the design engineers so that tolerances can be determined based on the ability of the manufacturing processes to meet them. The manufacturing capabilities should be fed back into the design to result in a more producible product, consistent with the inherent capabilities of the existing processes. Monolithic parts incorporating multiple individual parts can also impart tremendous benefit to the assembly process. There is a potential cost, however; monolithic parts may be more expensive to store, support, and replace later in the system lifecycle. Designers should balance lifecycle costs when making design trades.

5.2.1.1.3 Coordinating with Key Suppliers

When key suppliers are included as full members of the design team, the functional allocation and integration of all system components is enhanced. Producibility and affordability engineering practices should be flowed down to major/critical suppliers that retain design authority.

5.2.1.1.4 Post development producibility activities

When producibility issues drive post-baseline process changes, Process Improvement Plans should be formally documented. Documentation should include the baseline cost (before implementation), the post-implementation cost targets, as well as the non-recurring costs to implement the initiative.

5.2.1.1.5 Additional producibility resources

An excellent source of information on executing effective producibility programs is the DoD's Producibility and Manufacturability Engineering Guide. The guidelines recommend addressing the following six major activities:

1. Organizing to foster producibility
2. Planning to ensure component, assembly, and system designs are optimized for production
3. Concurrent Engineering approach that permits manufacturing experts to influence the design
4. Process Capability assessment and improvement efforts that pursue ever more mature and capable processes
5. Measurement & Improvement efforts that use fact-based decision making to drive manufacturing process improvement
6. Manufacturability/Manufacturing Operations that exploit advanced/digital manufacturing tools

5.2.1.2 Lessons Learned

Lessons learned regarding implementation of the producibility analysis best practice are presented in Table 11:

Table 11: Producibility Analysis Lessons Learned

#	Lesson Learned
1	One major DoD program discovered that requirements for a producibility program should not be placed on contract using a Firm Fixed Price option. Although an acceptable contractor level of effort for producibility activities was negotiated, once on contract, higher priority work at the prime contractor prevented the agreed-to level of effort from being accomplished. Since no specific producibility results or deliverables were specified in the contract, there were no executable consequences for failure to execute a good faith effort. As a result, the contractor recorded a high profit rate while the affordability and producibility of the product was not measurably improved. Instead of a Firm Fixed Price contract, a Cost Plus Fixed Fee contract is recommended.

Table 12: Producibility Analysis Lessons Learned – Continued

#	Lesson Learned
2	Even when producibility efforts are properly motivated by contract incentives, it is often difficult to distinguish initiatives that are “over and above” those already present in established improvement curves used to project future program costs. Improvement curves, by their nature, already anticipate cost reductions, some of which may be the result of “normal” cost improvement initiatives. The challenge in documenting and estimating the impacts of new projects, therefore, is to determine if they impact the improvement curve beyond what is already built into the existing, and therefore extrapolated/projected, learning curve path. Generally, initiatives that explicitly reduce the scope of standard work as a result of the funded initiative can be considered change beyond normal improvement; but the impact of improvement initiatives on efficiency of the work should be more carefully evaluated. The Lessons Learned for Continuous Improvement, presented in 5.5.3.2, provide insight into how another program handled this challenge. Producibility initiatives for the cargo floor of one aircraft program replaced 22 extrusions with eight machined parts. This change reduced fastener installations by 4,000 and netted $8.7 million in program savings.
3	Another program found returns on investment approaching 20 to 1 for initiatives implemented early in a program. As programs proceed through production, the return multiple is expected to decrease as the production units remaining diminishes in size. However, a program found the benefits do not decrease because it is the easy, low hanging fruit that is exhausted early. They continued to find and pursue producibility projects that resulted in large payoffs, demonstrating the importance of continuing producibility efforts even after the early rounds of producibility projects have been implemented.
4	Historically, efforts have relied on separate, serial product and process development activities, with most development emphasis placed on system performance during pre-production. When the required performance was functionally demonstrated, attempts were made to transition the design to production. The manufacturing function tried to adapt existing processes to manufacture the qualified design. Considering producibility earlier in the design process promises a smoother transition to production.
5	DA is a producibility approach that can significantly reduce tooling and assembly costs. Instead of relying on expensive tools and fixtures for part placement, DA incorporates self-locating features directly on mating parts. One Air Force program recently used this technique to align longerons with skins and bulkheads, reducing aircraft assembly time by 1,200 hours per shipset.

5.2.2 Key and Critical Characteristics

An effective MM Program identifies and manages key and critical characteristics as part of the technical data package. The KC/CC program identifies and manages KCs and CCs, traces KCs to Key Manufacturing Processes (KMP) and CCs to Critical Manufacturing Processes (CMP), flows down KCs/CCs to suppliers, and requires suppliers with design authority to manage their own KCs/CCs/KMPs/CMPs. The Pareto principle, as applied to the identification of key and critical characteristics, asserts that a relatively small number of design features will have a disproportionate impact on product performance. Application of this principle enables directing of scarce resources toward managing and improving the most critical product features and associated production processes. Viewed this way, management of key/critical characteristics is a cost containment activity, not a cost driver.

5.2.2.1 Guidance

The identification of key and critical product characteristics, and their subsequent association with production process capability assessments and improvement activities, is a basic engineering task essential to successful manufacturing development. The objectives of this practice are:

- identify product characteristics of the design which most influence fit, form, function, performance, service life, or human safety,
- support the mapping of product characteristics to production processes,
- enable the balancing of product design requirements with manufacturing process capabilities, and
- enable the development and implementation of required process control and process improvement efforts to ensure key product characteristics are produced as close to nominal as possible.

5.2.2.1.1 Identify KCs

To have the greatest impact, KC identification should begin in the earliest phases of product development, at which time a preliminary list of KCs should be produced. As the development phase continues, the KC/CC list should mature. As KCs firm up, the list of associated key process characteristics takes shape. The connection of key and critical product characteristics to key process characteristics triggers the development of process control plans, which prioritizes and instigates variability reduction efforts. Designers have used a wide variety of approaches to identify KCs. Subjective approaches, such as technical discussions and consensus among design and manufacturing experts may be used. More objective and rigorous tools are also recommended, including Design Failure Mode and Effect Analysis (DFMEA), Quality Function Deployment, detailed risk identification methods, or statistical analysis of yield and reliability data from similar products. KCs should be identified on drawings or in specifications. One method is to use flags, as shown in Figure 2. A unique identifier should be assigned to each KC so related data can be tracked and mapped to the production processes that create the KCs.

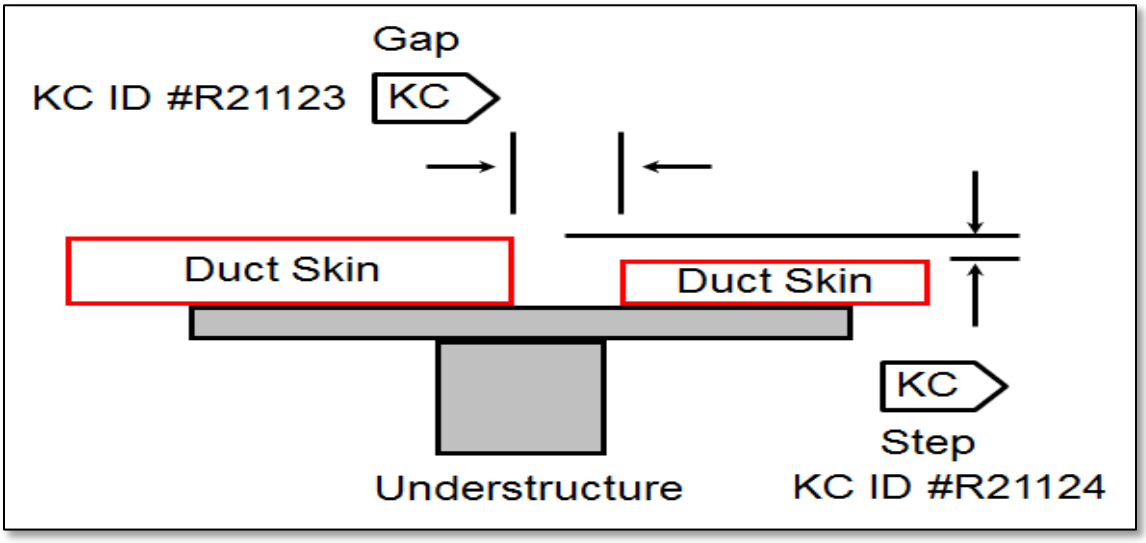

Figure 2: Sample KC flags on a drawing

5.2.2.1.2 Trace KCs to key processes

Once KCs have been identified, the development team should determine which manufacturing processes significantly contribute to the satisfactory production of each KC; these processes become designated as key processes. For each key process, key parameters should be identified. Key process parameters are process inputs (for example, temperature, time, pressure) that have a significant impact on the product and must, therefore, be strictly controlled. The contractor should maintain documentation clearly depicting the relationship between each KC and its associated key processes. A PFMEA should be performed, and process control plans should be developed and implemented, for each key manufacturing process. When KCs are identified for assembly characteristics (such as fit, gaps, etc.), the design for each part composing the assembly must be assessed to determine if KCs exist at the interfaces between the parts. Higher level KCs should be flowed down to the lowest necessary level to ensure controls in fabrication.

5.2.2.1.3 KCs and low production quantities

Some question whether KCs need to be identified on programs with very low production quantities. The answer to this question is yes; KCs should be identified regardless of the anticipated production quantities. The definition of KC is independent of quantity produced. If a characteristic is important, that feature needs to be communicated to the production floor, so it is treated with due care. Process control plans must still be developed to ensure the quality of the KCs on small production runs. The process control plans for some KCs may need to rely on small sample statistical process control methods; however, even if the overall production quantities are low some key processes may still be repeated hundreds or thousands of times (for example, hole drilling).

5.2.2.1.4 KC management flow down to suppliers

Prime contractors should have a plan for managing production of parts and assemblies possessing key characteristics produced by suppliers. Suppliers producing a design provided by the Prime Contractor should inherit responsibility for selecting capable processes when producing flowed-down key characteristics; those delegated design authority should be required to identify and manage KCs and critical processes.

5.2.2.1.5 Additional KC resources

Additional rationale and guidance on Key Characteristics can be found in Appendix B and in SAE's aerospace standard SAE AS9103, "Variation Management of Key Characteristics." SAE AS9103 is a philosophically consistent with the ideas presented in this handbook and SAE AS6500; it may therefore be included in SOWs to provide more robust requirements for KC and Variation Management.

5.2.2.2 Lessons Learned

Lessons learned regarding implementation of the key and critical characteristics best practice are presented in

Table 13: Key and Critical Characteristics Lessons Learned

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Table 13: Key and Critical Characteristics Lessons Learned

#	Lesson Learned
1	KCs serve as an excellent communication tool among organizations and suppliers; involving cross-functional (and often cross-company) representatives when determining critical interfaces and features can result in huge dividends. On one major airframe program, effective KC communication resulted in major structural sections “fitting like a glove” despite being designed and produced by geographically separated entities using different materials and processes.
2	Key characteristics should include those derived from CCs. A recent IRT discovered that reviewed design documentation did not consistently consider and include safety-critical features in the identification and selection of KCs. As a result, no special emphasis on CCs was communicated to manufacturing, quality, purchasing, or the supply chain.
3	Because each KC introduces production process monitoring and management costs, identification of large quantities of KCs can prove troublesome. Identification of an excessive number of KCs can result when a product design engineer (1) misunderstands the definition of KCs, or (2) misunderstands the purpose of KCs (for example, perceives KCs as an opportunity to require collection of additional manufacturing data). On one large aircraft program, product design engineers flagged weight as a KC, not because it legitimately possessed attributes of a KC, but because doing so imposed a requirement to capture additional, desirable weight-related manufacturing data.
4	Initial design tolerances for KCs should reflect known process capability limitations. Data[8] from similar parts and processes should be available to inform designers of the tolerances that can be maintained with existing shop floor production process/capabilities. If indications are that associated key manufacturing process cannot reliably reproduce a product KC, the designers should consider a redesign that eliminates the product feature or, at a minimum, makes it more robust and less sensitive to variation. Design modifications are nearly always more cost-effective than upgrading the factory or acquiescing to the cost of poor quality.
5	Tracking the total number of KCs identified to-date may be informative; but responding to changes in counts of activity (that is, responding to any form of unnormalized data) is contrary to sound metric design practice. Counts of KCs fluctuate naturally over the course of a product development program. Early in a product development program, KC counts rise as new KCs are identified; KC counts may subsequently drop as the design matures and some KCs are consciously eliminated during the design maturation process (for example, two parts are redesigned as one, eliminating what was a key interface). KC count fluctuations therefore need not drive “corrective actions”; the true objective of KC identification is to select (when available) or develop/improve (when not available) processes capable of producing each KC.
6	Remember to consider all potential sources of KCs. For example, KCs may be derived from non-dimensional features such as: (1) mechanical aspects of the parts (for example, solder characteristics, part dimensions) that could impact the integrity of the part or its physical integration into the next higher assembly, and (2) electrical performance parameters (for example, voltage range, activation time, frequency response).
7	Product design tools like DA aid in the identification of candidate key characteristics and support design decisions that may eliminate many candidates before the design is complete. However, not every design decision truly eliminates the KC, some only mask them. For example, tightening dimensional tolerances beyond “normal” means specific, exceptional design action is being taken to ensure an attribute or feature is closer to nominal than “normal” tolerances would guarantee. This tolerance tightening action effectively represents a control mechanism that should be described in a control plan. Tightened design tolerances, when viewed in this light, are perhaps best considered more an indicator of KCs than an eliminator of them.

[8] Many contractors have captured impressive quantities of process capability data over time and have made it available in databases or design handbooks.

5.2.3 Process Failure Mode and Effects Analysis

An effective MM Program performs PFMEA as part of the design and development process, and to identify and prevent or mitigate failures, minimally on KMPs (including the subset of KMPs associated with CCs, also called Critical Manufacturing Processes (CMP)). PFMEA identifies foreseeable modes of failure inherent within a process design, with special emphasis on catastrophic and safety related failures. Inadequacies of existing manufacturing processes can then be addressed during manufacturing process design. Conducting a PFMEA during process development permits early problem identification and resolution, focusing on prevention of non-conformances rather than detection. Potential manufacturing failure modes, identified early enough, may drive more robust product designs less sensitive to manufacturing processes variation. Reducing failure points increases product quality and reduces production, operations, and maintenance costs. PFMEAs are especially valuable to analyze critical manufacturing processes where the PFMEA prevents defects that are most relevant to safety and mission performance of the part or system. They can also be used to reduce cost on high dollar value parts and parts with manufacturing processes that have a high scrap and/or rework cost. DoD, prime contractors, and suppliers should realize the following benefits:

- increased quality because of a more thoroughly engineered manufacturing process.
- cost savings by reduction of rework
- cost reduction by identification of potential errors earlier in the life of the system.
- better understanding of the effects of potential failures on the customer
- upgraded production performance from process improvement efforts based on a prioritized list of potential failure modes
- improved Customer Satisfaction due to the development of products with greater quality and reliability

5.2.3.1 Guidance

Initiate PFMEA as soon as the product design has sufficiently matured to initiate manufacturing process development. After the initial PFMEA has been completed, it should be updated when (1) a new process is introduced, (2) an existing process is modified, (3) an existing process is to be used in a new environment, location or application, or (4) when a new failure mode is identified during production. The level of effort, sophistication, and scope of a PFMEA should be thoughtfully tailored to each application. An Ishikawa cause and effect (a.k.a. “fishbone”) diagram may be used to help identify the potential causes of failures (for example, potential failure modes) and their effects. Development and maintenance of PFMEA process worksheets is important to ensure continuity for follow-up analysis. It is important to recognize that PFMEAs cannot improve the quality or reliability of an inherently poor design. DFMEA is a similar failure mode analysis technique used to identify potential problems with the product design and to eliminate or mitigate those problems before the design is finalized. PFMEAs, with their focus on manufacturing process design, are therefore not intended to take the place of DFMEAs. Manufacturing and Quality Engineers should contribute to DFMEAs early in development, and outputs from the DFMEA should feed into the PFMEA to provide the most robust transition to production.

PFMEAs should be accomplished by analysts familiar with the manufacturing processes and technologies being used. Treating PFMEAs as box-checking, CDRL-fulfilling exercises will effectively defeat their purpose. Therefore, teams assigned to accomplish PFMEAs should take care to avoid common pitfalls described in Table 14.

Table 14: PFMEA pitfalls to avoid

#	Pitfall	Mitigation Recommendation
1.	Untimely undertaking	The PFMEA should be scheduled and completed concurrently with the design of the manufacturing and assembly process so that the product designs will reflect its analysis, conclusions, and recommendations.
2.	Insufficient Recognition of Failures and Causes	The discovery of failures and their causes is essential to the PFMEA task. Potential failure modes should be explained and not simply named. Make sure failure modes are not confused with effects or causes. An understanding of the process functional requirements is requisite to understanding potential failure modes, effects, and their causes.
3.	Failure to properly identify the customer	The customer will not always be the end user; the customer may be downstream manufacturing or assembly operations.
4.	Too narrow in scope of analysis	The contractor should explore the effects of multiple failures, degraded conditions, and downstream effects. After establishing potential failure modes for a particular process, consider the effects in relation to the entire system and all customers.
5.	Weak recommendations	Ensure recommend actions actually resolve the risk; develop solutions that are executable.
6	Improper failure classification	Potential failure modes should be accurately classified. Trivializing or hiding potential safety items or failure modes must be avoided. Similarly, ensure occurrence and detection are not treated with too much optimism.
7.	Ignoring existing system data	Failure data and history of very similar systems should be considered.

5.2.3.1.1 PFMEA methodology

PFMEA provides a structured methodology for identifying, analyzing and mitigating (to include preventing, when possible) failures in manufacturing and assembly processes. PFMEAs should be accomplished early during conceptual design and updated regularly throughout product development. The steps in performing PFMEAs[9] are:

- identify potential process failure modes and the effects of those failures.
- assess the probability and consequences associated with failure modes; and
- develop actions that will mitigate or eliminate the probability and/or consequences of the potential failures.

5.2.3.1.2 Elements of a PFMEA

A PFMEA should address the ten elements shown in Table 15.

Table 15: Elements of a PFMEA

#	Element	Description
1.	Process Function	A concise statement of the manufacturing process function (for example, polishing, deburring, drilling, assembling). Supporting information should be included to provide context. Indicate the purpose of the process and include metrics for performance.

[9] Some literature on FMEAs (of either the design or process kind) includes criticality analysis of each of failure modes being analyzed to determine which are most important. When this is incorporated into the analysis, it becomes Failure Mode, Effects and Criticality Analysis (FMECA). When developing SAE AS6500, the SAE committee elected not to impose criticality analyses. Therefore, SAE AS6500 requires PFMEA, but remains silent on Process Failure Mode, Effects, and Criticality Analysis (PFMECA).

Table 16: Elements of a PFMEA – Continued

#	Element	Description
2.	Potential Failure Mode	A specific way in which the part can fail to meet specifications or otherwise dissatisfy the customer. Describe the potential failure as a physical nonconformance of the process output (for example, bent, cracked, handling damage, hole off-location). All anticipated failure modes for each component, sub-system and process characteristic should be identified and described.
3.	Failure Effects	The consequences to the customer for each potential failure mode. The failure under consideration may affect multiple levels of the system. Because of this, local, next higher level, and end effects should be evaluated. For each level of the system, also consider each customer. The local effect is typically the failure mode itself but may also be stated in terms of effects on the local process (for example, cannot assemble, damages equipment, causes excessive tool wear, endangers operator). For downstream manufacturing operations, failure effects should be stated in terms of process performance. End effects are those experienced by the user, and the effect a failure mode has on the operation, function or status of the global manufacturing process. These effects should be stated in terms of product or system performance (for example, excessive noise, intermittent operation, rework/repairs, poor appearance).
4.	Severity	A numerical rank given to each failure effect. It considers the worst potential consequence of a failure, determined by degree of injury, interruption to the process, or damage to the system. Though philosophically subjective, the PFMEA team should agree on standard ranking criteria appropriate to the analysis. The ranking criteria should create categories of failure effects (for example, minor, marginal, critical, catastrophic). The categories should then be assigned a numerical rank. The appropriate numerical rank should then be assigned to each failure effect.
5.	Causes	A description of the potential causes of a failure mode, written in terms of something that can be controlled or prevented (for example, inaccurate gauging, worn locator, improper heat treating, inadequate lubrication). Avoid ambiguous naming of causes (for example, operator error, machine malfunction). Causes will often be interrelated, and a design of experiments or similar method may be necessary to discover major causes that can be controlled.
6.	Occurrence	The probability that a specific failure mode will happen. Occurrence is numerically ranked in the same manner as severity. Historical failure rate data should be used if it is available. Statistical data from similar processes can be used as a basis for determining occurrence. If similar historical data is not available, the team may be required to initially perform a subjective assessment.
7.	Current Process Controls	Existing controls that either prevent or detect potential failure modes. Prevention controls are preferred and may include methods such as SPC or error proofing. Detection controls may include gauging, manual inspection or process inability to pass a bad part.
8.	Detection	The probability that a failure will not be detected. Detection is numerically ranked in the same manner as severity and occurrence. The probability of non-detection is established in the same manner as occurrence.

Table 16: Elements of a PFMEA – Continued

#	Element	Description
9.	Risk Priority Number (RPN)	Represents failure mode criticality. This is a simplified but effective version of criticality analysis. The RPN is the product of severity (S), occurrence (O), and detection (D): $RPN = S \times O \times D$ The potential failure modes with the highest RPNs are the most critical and deserve the most attention. Items with very low RPNs may not warrant action.
10.	Recommended Actions	Should be developed with the purpose of lowering the RPNs. Once the highest RPNs are addressed, the team can continue to address the next highest risk areas. The actions should endeavor to reduce rankings in the following preference order: severity, occurrence, and detection. Emphasis should be placed on preventing failures rather than detecting them.

5.2.3.1.3 Additional PFMEA resources

An industry standard method for conducting PFMEAs can be found in the Society of Automotive Engineers (SAE) J1739, “Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)”. Another source of information is the document titled “Potential Failure Mode and Effects Analysis” from the Automotive Industry Action Group. Finally, SAE ARP 5580, “Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications” is an additional available resource.

5.2.3.2 Lessons Learned

Lessons learned regarding implementation of the PFMEA best practice are presented in Table 17:

Table 17: PFMEA Lessons Learned

#	Lesson Learned
1	PFMEA analysis, conducted in a timely manner, can identify and drive failure mode elimination efforts before the failure modes become an intrinsic part of the production process baseline. Alterations to manufacturing processes or improvements to product designs based on PFMEA performed early in the development phase are more easily implemented at a lower cost. When design or process changes are implemented, the analysis and associated documentation should be updated.
2	PFMEAs can be used to identify opportunities to “poka-yoke” (mistake-proof) manufacturing processes; foreseeable modes of failure with high-risk priority numbers should, as part of their recommended actions, include mistake-proofing devices or processes. The findings of numerous government independent reviews indicate mistake-proofing is an underused approach; even a modest implementation of poka-yoke concepts may have prevented several high-profile weapon system failures.

5.3 Manufacturing Risk Identification

There are three best practices associated with Manufacturing Risk Identification: (1) Manufacturing Feasibility Assessments, (2) Manufacturing Readiness Level (MRL) Assessments, and (3) Production Readiness Reviews (PRR). Each of these practices, which will be addressed in the following subparagraphs in turn, provide input to an acquisition program's broader risk management activity as identified in the DoD "Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs".

5.3.1 Manufacturing Feasibility Assessments

An effective MM Program accomplishes manufacturing feasibility assessments prior to selecting a preferred product design solution. Manufacturing Feasibility Assessments are most effectively performed early in a product's life cycle when competing design concepts are still being considered. The assessments identify design alternative manufacturing risks and constraints and measure a contractor's ability to execute required manufacturing efforts.

5.3.1.1 Guidance

Manufacturing Feasibility Assessments should be accomplished for each product design alternative under consideration. Specifically, they should:

- Identify required production processes and manufacturing techniques not currently available and the risks associated with their development, the probability of meeting the need dates, and possible contingency actions.
- Identify potential impacts of critical and long lead time material and production equipment, the probability of meeting the need dates, and possible contingency actions.
- Provide production feasibility, design performance, cost, and schedule impact analyses to support trade-offs among alternatives.
- Provide cost and production schedule estimates to support management reviews.
- Determine an efficient rate of production and rate acceleration curve.
- Make recommendations for anticipated production testing and demonstration efforts, including specific requirements for production run demonstrations using production tooling, test equipment, and manufacturing equipment.
- Identify methods of conserving critical and strategic materials and to reduce reliance on foreign sources.
- Identify potential production bottlenecks and other limiting factors to rate production.

5.3.1.2 Lessons Learned

Lessons learned regarding implementation of the Manufacturing Feasibility Assessment best practice are presented in **Table** 19.

Table 18: Manufacturing Feasibility Assessment Lessons Learned

#	Lesson Learned
1	State-of-the-art enhancements incorporated into both development and manufacturing may be sources of opportunity but may carry potential sources of high risk. During Manufacturing Feasibility Assessments, it is essential to carefully evaluate the state-of-the-art enhancements and technology insertions for each design alternative and their associated manufacturing processes. Because new technology tends to stretch a contractor's technical capabilities, additional attention should be given to assess the manufacturing feasibility of the state-of-the-art processes and their potential to meet required production volumes. Recognize that an opportunity for one contractor may be a risk for another. Risks may be mitigated by selecting a contractor focused on the design and performance characteristics and another contractor or subcontractor that has more experience with manufacturing the state-of-the-art technology and is focused on the controls, equipment, and processes required.

5.3.2 Manufacturing Readiness Level Assessments

An effective MM Program uses MRL criteria to accomplish assessments of manufacturing risk and maturity. MRL assessments were developed by the Office of the Secretary of Defense's (OSD) Joint Defense Manufacturing Technology Panel (JDMTP). As described in the MRL Deskbook, they aid in the assessment of manufacturing readiness by stratifying manufacturing readiness into ten maturity levels. The intent is to provide a standardized measurement scale that serves the same purpose for manufacturing readiness that Technology Readiness Levels (TRL) serve for technology readiness, which is to provide a common metric and vocabulary for assessing and discussing manufacturing maturity, risk, and readiness. MRL numbering and phasing roughly parallels TRLs, as shown in Figure 3.

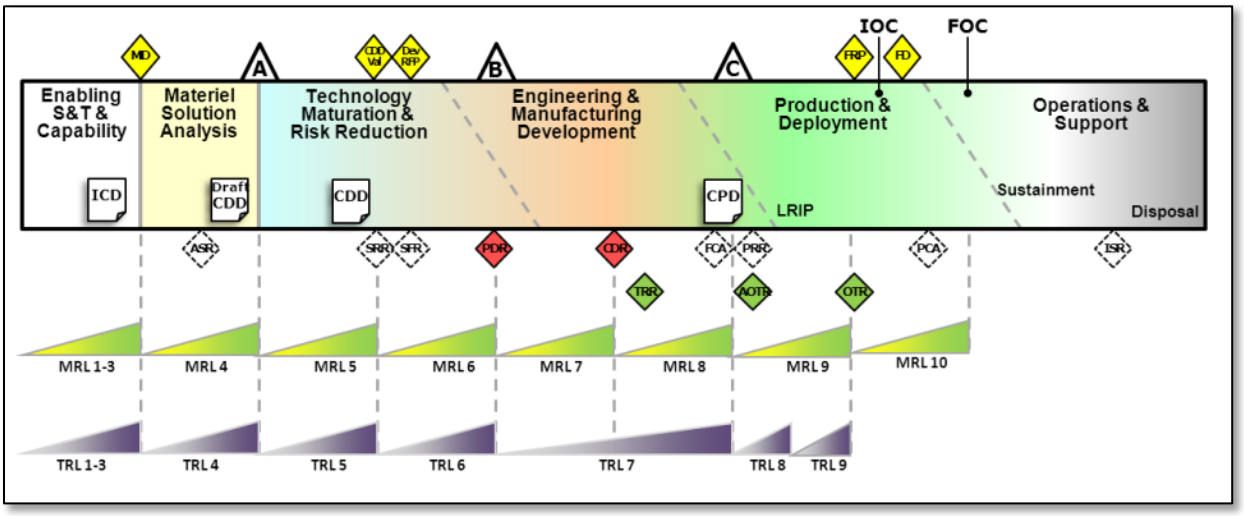


Figure 3: Relationship of MRLs to TRLs and acquisition milestones

Manufacturing readiness, like technology readiness, is essential to the successful introduction of new products and technologies; MRLs are an effective tool to address that need. MRLs are designed to provide decision makers, using a standards-based approach, an understanding of the attendant risks associated with manufacturing technologies and processes being considered to meet DoD product requirements.

5.3.2.1 Guidance

In defense acquisition, issues arise when the acquisition team overestimates technology readiness, downplays potential transition to production problems, or fails to plan and perform effective risk management; consequences include technical compromises, schedule delays, and cost overruns. MRL Assessments have been used to successfully identify and mitigate manufacturing risks. An MRL Assessment is a snapshot of manufacturing maturity at a moment in time. MRLs should be performed on an ongoing basis, in parallel with a program's technical development (for example, in concert with planned technical reviews/baselines and as part of the program's risk management process). Manufacturing Readiness Level criteria are organized into categories called "threads" (for example, Design, Materials, Process Capability & Control). Recall that MRL threads trace to SAE AS6500 requirements (Table 6). Implementing the best practices described herein will therefore support successful achievement of target MRLs. Objective criteria are provided for each MRL to reflect the mounting expectation of maturity as the program progresses through its life cycle. During early program phases, manufacturing feasibility is the focus of expectations. As a program progresses into and through development, the MRL expectations become more defined and concrete. As the design approaches its mature product baseline, production representative manufacturing processes are required. At the completion of the EMD phase (that is, at the time of the Production Readiness Review), programs should be making use of the same tooling, test equipment, workforce, work instructions, and methods planned for the Production phase. MRLs may also be accomplished on an ad-hoc basis; they can serve as special, targeted reviews of manufacturing capability when needed. See www.dodmrl.com for additional, detailed guidance on MRLs and MRL Assessments.

5.3.2.2 Lessons Learned

Lessons learned regarding implementation of the MRL best practice are presented in Table 19:

Table 19: MRL Lessons Learned

#	Lesson Learned
1	One specific MRL success story involves an Air Force bomber modification program. Program office personnel, in conjunction with the prime contractor, assessed a dozen key suppliers and identified numerous risk areas that required risk mitigation plans. The identified risks ranged from product-oriented actions (for example, design changes, diminishing manufacturing source issues) to factory process improvements (for example, quality and production control systems). The program office asserts many of the risks would not have surfaced until the program started production, resulting in cost and schedule impacts, had the MRL process not been in place.
2	MRL Assessments also provide benefits to prime contractors and their suppliers. When there is limited government program office manning, government engineers and program managers may not be aware of issues at lower tier suppliers; prime contractor MRL Assessments provide an avenue for highlighting previously undisclosed supplier issues that can be elevated to the program office for assistance. For example, on another Air Force bomber modification program, an MRL assessment revealed diminishing manufacturing source issues at suppliers that required government action for resolution. Furthermore, an MRL Assessment for an item of personal protection equipment identified the need for additional manufacturing technology development; the program office allocated additional funding to improve manufacturing process yields, which improved schedule confidence and reduced cost.

5.3.3 Production Readiness Reviews (PRRs)

A PRR is one of eight formal Systems Engineering Technical Reviews identified in OUSD R&E Systems Engineering Guidebook. An effective MM Program conducts PRRs prior to, and in support of, production milestone decisions (for example, low-rate initial production, full rate production). The PRR is an on-site, structured examination of the contractor's readiness for production. PRRs are used to assess whether prime contractors and their major suppliers have performed adequate production planning, thereby confirming there remains no unacceptable risk to successful achievement of schedule, performance, and cost objectives as the program transitions from development to production.

5.3.3.1 Guidance

A thorough assessment of a contractor's manufacturing maturity and risk, led by manufacturing subject matter experts, is the desired outcome of a PRR. A PRR should include comprehensive evaluations of the MRL threads shown in Table 6: MRL threads to MM Program requirements cross-reference (tailored appropriately); a PRR supporting an LRIP milestone should assess readiness against MRL 8 criteria while a PRR supporting a FRP milestone should assess readiness against MRL 9 criteria. These PRR MRL targets should be reflected in the acquisition program baseline. The PRR report includes a recommendation to the Milestone Decision Authority regarding a program's readiness to proceed past Milestone C to the production phase. In incremental acquisitions (that is, programs that release strategically planned subsets of functionality in increments over time rather than all at once at the completion of a monolithic development phase), PRRs should be conducted for each major product increment. PRRs should also be conducted whenever major changes to the contractor's production system warrant additional review, even if they occur after the full-rate milestone decision. Examples of changes that might trigger a follow-on review are movement of the production facility, large-scale tooling changes, major supplier changes, and/or the onset of significant production problems.

5.3.3.2 Lessons Learned

Lessons learned regarding implementation of the PRR best practice are presented in Table 20:

Table 20: PRR Lessons Learned

#	Lesson Learned
1	The assessment of manufacturing readiness should highlight where key program-level manufacturing preparations fall short of MRL 8 (LRIP) or MRL 9 (FRP) requirements. The PRR Report should address the risks that these deficiencies pose to the program and estimate/plan for the schedule or funding changes required to mitigate them. The plan to mitigate deficiencies should be documented in Manufacturing Maturation Plans and tracked to completion.

5.4 Manufacturing planning

There are nine MM Program requirements associated with Manufacturing Planning: (1) Manufacturing Plan, (2) Materials Management, (3) Manufacturing Technology Development, (4) Cost, (5) Manufacturing Modeling and Simulation, (6) Manufacturing System Verification, (7) Manufacturing Workforce, (8) Tooling/Test Equipment/Facilities, and (9) Measurement System Analysis (MSA). Each of these requirements will be addressed in turn.

5.4.1 Manufacturing Plan

An effective MM Program produces and maintains a manufacturing plan. As emphasized in Section 5.1, the first step toward ensuring successful production execution is to develop documented planning that describes how manufacturing excellence will be pursued and achieved. The program office should require the contractor to produce and make available for review manufacturing planning documentation that details, minimally, how the requirements and best practices of SAE AS6500 will be addressed.

5.4.1.1 Guidance

Manufacturing Planning documentation should be developed prior to Milestone B, when possible, but not later than early EMD (that is, coincident with PDR). The program office should require updates to the planning documentation throughout the EMD and production phases. The latest revision of DI-MGMT-81889, "Manufacturing Plan" may be cited in the contract as a template for manufacturing planning documentation. This template requires the contractor to "*provide an integrated collection of the processes, policies, business systems, and other tools required to plan, execute, and manage manufacturing operations, including the integration of corresponding supplier activities*."

5.4.1.2 Lessons Learned

Lessons learned regarding implementation of the Manufacturing Plan best practice are presented in Table 21:

Table 21: Manufacturing Plan Lessons Learned

#	Lesson Learned
1	Requiring a formal, documented manufacturing plan as a deliverable provides added attention and focus to manufacturing planning. It affords program office manufacturing engineers the opportunity to review the contractor's manufacturing approach to ensure it comprehensively addresses effective MM Program requirements.

5.4.2 Materials Management

An effective MM Program assesses supplier capability and stability, to include identifying risks associated with single and foreign sources. Materials management involves management of key and critical parts (see Section 0), plans to identify, conserve, minimize waste of, and reclaim strategic and critical materials, management of Diminishing Manufacturing Sources and Material Shortages (DMSMS), and prevention of counterfeit parts. Supporting defense weapon systems throughout their lifecycle often requires the production, storage, and use of parts for decades. Over time, the number of sources available to supply needed weapon system parts may drop to a single domestic source[10], or to no domestic source at all.

5.4.2.1 Guidance

The material scarcity phenomenon, branded DMSMS, makes acquiring parts that meet Original Equipment Manufacturer (OEM) specifications particularly challenging for DoD. Special challenges also arise from an undesirable reliance on foreign sources, including the possible compromise of security introduced by counterfeiting. The following paragraphs elaborate on the risks caused by DMSMS and counterfeit parts and strategies for addressing them.

[10] For example, OEM, authorized aftermarket manufacturer, or franchised/authorized distributors

5.4.2.1.1 Risk associated with single sources of materials: DMSMS

The loss or impending loss of sources of items, material, or software, known as DMSMS, surfaces when a single source announces discontinuation of a product or when a procurement otherwise fails because of product unavailability. DMSMS endangers the life-cycle support and viability of weapon systems, spares, and support equipment. Compared with the vast commercial electronics sector, the DoD is a minor consumer of electronic devices. This, combined with the fact that the DoD regularly seeks to prolong the life of its weapon systems, exacerbates DMSMS problems as spare parts and materials disappear from the marketplace before the weapon system reaches the end of its life cycle. While experience has demonstrated that electronics are the most likely items to be discontinued, obsolescence of non-electronic and COTS items also presents challenges. The adverse impacts of technology obsolescence and diminishing manufacturing sources on the cost and performance of our Weapon Systems appears to be growing. This may be triggered, in part, by the accelerated rate of technological change (especially in electronics), our growing dependence on commercial sources, and the extended development time and operational life of our systems.

5.4.2.1.1.1 Addressing risk associated with single sources of materials: DMSMS

Managing DMSMS is a complex, data and resource intensive process. DoD policy prescribes a proactive DMSMS approach that addresses each of the following:

- Ensures that all parts and material to produce or repair the system are available
- Reduces, or controls, total ownership cost (TOC)
- Minimizes total life-cycle systems management (TLCSM) cost
- Eliminates, or at least minimizes, reactive DMSMS actions
- Evaluates design alternatives
- Provides for risk mitigation as it applies to DMSMS
- Evaluates more than one approach to resolve DMSMS issues
- Collects metrics to monitor program effectiveness

5.4.2.1.1.2 Bill of Materials

A Bill of Materials (BOM) is a list of parts and materials needed to produce a system, subsystem, or assembly. An indentured BOM shows the relationship (generally in hierarchical form) of system components; for example, flight computer components would be shown from resister, to board, to black box, and ultimately to its placement in the system. Ideally, the BOM will be made available in an editable electronic open-standards format. The BOM is an indispensable resource that enables proactive DMSMS management. Without it, impact analysis, component analysis, prediction of discontinuance, and other DMSMS-related management activities would be much more difficult.

5.4.2.1.1.3 DMSMS management

The level of DMSMS management should not be the same for every weapon system; one size does not fit all. Programs should consult their contractors, suppliers and SMEs within DoD to design an appropriately scoped, effective DMSMS management approach.

5.4.2.1.1.4 Additional information

The Defense Standardization Program Office has published SD-22, “Diminishing Manufacturing Sources and Material Shortages – A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program”11 This guidebook provides best practices for implementing effective DMSMS program throughout a program’s lifecycle.

5.4.2.1.2 Risk associated with foreign sources of material: counterfeit parts

Supply chains are critical components of any large, geographically dispersed enterprise. Careful attention must be paid to the quality and authenticity of supplies entering the enterprise; failure to do so could introduce vulnerabilities that compromise the mission. The DoD draws from a large network of suppliers across an increasingly global supply chain; limited visibility into foreign sources increases the risk of inadvertently procuring counterfeit parts. According to the Government Accountability Office (GAO), the rise of counterfeit parts is one of several growing challenges the DoD faces in addressing part quality problems. Counterfeit parts have the potential to seriously disrupt DoD supply chains, delay missions, affect the integrity of weapon systems, thereby endangering the lives of our warfighters. Profit appears to be a significant incentive for counterfeiting in both the commercial and defense sectors. However, long life cycles that spawn DMSMS (for example, the B-52 went into service in February 1955 and currently has an anticipated retirement date of 2040) makes aerospace and defense products even more vulnerable to counterfeiting.

5.4.2.1.2.1 Addressing risk associated with foreign sources of material: counterfeit parts

A comprehensive counterfeit parts program should address, as a minimum, (1) requirements, (2) prevention, (3) detection, and (4) reporting, as shown in Table 22.

Table 22: Elements of a comprehensive counterfeit parts program

Element	Guidance
Requirements	Effective contract language focuses contractors on taking proactive counterfeit part prevention and mitigation courses of action. Following is an example of SOW language focusing on counterfeit part prevention: “*The Contractor shall develop and implement a Counterfeit Parts Prevention (CPP) Program in compliance with SAE AS5553 to prevent the inclusion of counterfeit parts or parts imbedded with malicious logic into products intended for sale to the government. As part of CPP, the contractor shall provide Certificates of Conformance (CoC) as well as acquisition traceability for Original Component Manufacturers (OCMs) and franchised/distributors in the supply chain, for example Certificates of Conformance and Traceability (CoCT). As an alternative to a stand-alone CPP, the elements of DI-MISC-81832 may be included in the Program Protection Plan (PPP).*”

[11]Guide may be accessed at:
https://quicksearch.dla.mil/Transient/B95C1B1E9F034AAAA137520ECDCD8073.pdf

Table 22: Elements of a comprehensive counterfeit parts program

Element	Guidance
Prevention	• The Government and contractors should procure parts directly from OEMs/OCMs and authorized distributors, rather than parts brokers, independent distributors, or the gray market. Contractors should notify government program managers when parts are obtained from other than OEM or authorized distributors. • Prime contractors should specify flow down of applicable requirements to include AS5553 to lower tier suppliers and maintain processes to verify such requirement. • Contractors should use robust quality management systems (for example, AS9100 for equipment providers and AS9120 for distributors). • Contractors should conduct surveys of their suppliers' inspection and testing capabilities and audit their counterfeit prevention program. • Traceability is a key means for verifying legitimate parts in any supply channel. Organizations should require their suppliers to trace parts back to OEMs/OCMs in order to prove part authenticity. • All requirements should be communicated to an organization's suppliers instead of assuming that suppliers take unilateral actions to prevent counterfeits. • The government should benchmark other companies and suppliers and pool information on anti-counterfeiting strategies. Contractors should benchmark and share best practices within their own supply chain. • Contractors should maintain a register of approved suppliers, including the scope of the approval, to minimize the risk of counterfeit parts supply.
Detection	Prime contractors and suppliers should conduct training in Counterfeit Parts Avoidance for Inspectors, Operators, Auditors, and lower tier suppliers to include awareness of AS5553. Training should discuss how to inspect parts and identify possible counterfeits (for example, non-conforming part markings). Prime contractors and suppliers should institute strong incoming quality assurance on all parts and visually inspect. Paperwork is not a substitute for testing. Prime contractors should require certificates of conformance, testing certification, and procedures for handling any counterfeit parts that slip through the system. Processes should specify methods for physical identification, segregation/quarantine, and control of suspect or confirmed counterfeit parts to preclude their use or installation. These processes should ensure the counterfeit parts do not re-enter the supply chain. The documented processes should ensure detection of counterfeit parts prior to formal product acceptance. Contractors should assess potential sources of supply (electronic parts, assemblies, and equipment suppliers) to determine the risk of receiving counterfeit parts. Assessment actions may include surveys, audits, review of product alerts (for example, Government-Industry Data Exchange Program (GIDEP), Electronic Resellers Association International (ERAI)), and review of supplier quality data to determine past performance. If items are confirmed to be counterfeit, contractors should not return the part to the actual or potential supplier at any time prior to criminal authorities' release of disposition.

Table 22: Elements of a comprehensive counterfeit parts program

Element	Guidance
Reporting	• Reporting processes should ensure all occurrences of counterfeit parts are reported to internal organizations, customers, government reporting organizations (for example, GIDEP), industry supported reporting programs (for example, ERAI), and criminal investigative authorities. • When contractors are notified by their suppliers regarding a suspect or a confirmed counterfeit part, they should notify the program offices as soon as possible (within 30 days of the original notification). • Suspected counterfeit material should be submitted, analyzed, and dispositioned using the Joint Deficiency Reporting System (JDRS). Additional information about JDRS can be found at www.jdrs.mil.

5.4.2.2 Lessons Learned

Lessons learned regarding implementation of the Materials Management best practice are presented in Table 23.

Table 23: Materials Management Lessons Learned

#	Lesson Learned
1	In recent years, nascent commercial demand for materials or components historically used exclusively in defense systems out-prioritized DoD demand in the marketplace. For example: a. Graphite Carbon Fiber composites used in low observable airframe manufacturing. Increased demand for graphite in the sport and entertainment industry (for example, golf clubs, tennis racquets) stretched lead times until additional production facilities came online to accommodate the increased demand. The best strategy in this case was early anticipation of military and commercial needs for graphite making it possible to lock up production capacity options with the main suppliers in advance. b. Liquid Crystal Displays (LCDs) used in avionics components. The explosion in the personal communications and entertainment industries (that is, cell phones, gaming consoles) led to reduced manufacturer interest in pursuing DoD contracts for electronic components. LCD production runs for a new fighter program numbering only several hundred units were not as attractive when commercial orders for purchase quantities for modern electronic components numbering in the millions were waiting. One strategy to counter this challenge has been to increase purchase quantities by standardizing DoD components across multiple platforms (even across military services) when possible. Another strategy has been to take greater advantage of commercial equivalent parts.

5.4.3 Manufacturing technology development

An effective MM Program determines if new or unproven manufacturing technologies will be required to satisfy program requirements. The DoD, in its pursuit of superior national defense, and in response to emerging threats, finds itself engaged in cutting edge product development. Cutting edge products often need cutting edge processes; failure to convert technologies into products is not an option. Producibility analysis, expertly conducted, will highlight those production challenges requiring cutting edge processes; sometimes the necessary unproducible product features cannot be eliminated by a design change. When this situation materializes, manufacturing technology development offers a possible solution.

5.4.3.1 Guidance

In response to the product/process maturation disconnect that can occur when cutting edge products encounter the production floor, the DoD established the Manufacturing Technology (MANTECH) program. The program's stated mission is "*to reduce the acquisition and supportability costs of defense weapon systems and reduce manufacturing and repair cycle times across the life cycles of such systems*." It is composed of the Military Service and DoD Agency investment programs operated out of the Army, Navy, Air Force, DLA, Missile Defense

Agency (MDA), and OSD. There are also nine DoD Manufacturing Innovation Institutes (MII) that are part of the national Manufacturing USA initiative that brings together industry, government, and academia partners to increase U.S. manufacturing competitiveness (Figure 4).

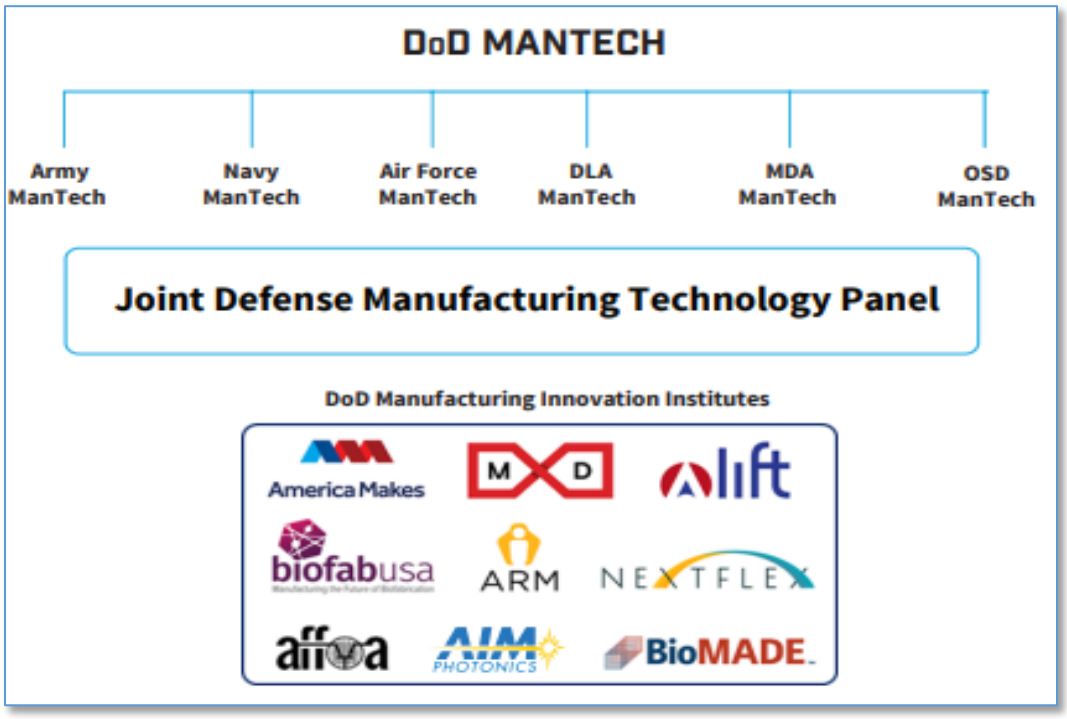


Figure 4: DoD MANTECH organization

Program offices should contact their cognizant MANTECH office for assistance with manufacturing technology expertise and possible manufacturing technology development funding[12].

[12] Source: DoD Manufacturing Technology Program (dodmantech.mil)

5.4.4 Cost

An effective MM Program develops and maintains a Production Cost Model (PCM). Because cost realism and credibility are of primary concern in a budget constrained, public trust environment, reliable cost models can be very useful. PCMs should minimally address known design-driven production cost elements early in development; they should then be updated regularly to reflect maturing product designs and associated production plans. A carefully constructed PCM serves a variety of uses:

- Projecting production costs against specified threshold affordability targets; assessing development program progress toward meeting production cost objectives and advising major milestone decisions.
- Predicting, assessing, and controlling production cost impacts of design changes, production rate changes, delivery schedule changes, alternate production processes, and proposed process improvements.
- Supporting broader finance and contracting processes (for example, independent program estimates, proposal preparation, fact-finding/negotiations, budgeting, and what-if exercises).

5.4.4.1 Guidance

A variety of analysis procedures may be considered when developing the PCM (for example, parametric, historical, analogy, detailed engineering estimates); selection of the most appropriate procedure depends on factors such as data availability and maturity of candidate product designs. Not all PCMs must be developed from scratch; commercial cost models are now available that can be adapted to accommodate company-unique accounting systems. Model parameters should be defined and incorporated early, for example, constant versus then-year dollars, production quantities and rates, and fiscal year budget constraints. Production quantities and rates are necessary to calculate return on capital equipment investments and other cost reduction initiatives. Production quantities and rates should be specified as ranges around a target to allow understanding of the model's sensitivity to rate changes, thereby reducing the risk of settling on a "point" design solution. Since the quantity and rate assumptions may have a significant impact on the final design and resultant production cost, they should allow testing the full range of realistic scenarios. The model should also account for ST, STE, SE, Government Furnished Property (GFP), sustaining engineering, and tooling as well as inspection, test, scrap, rework, and repair activities. The PCM level of detail and complexity will vary based on a variety of factors, including product complexity and program size/phase.

5.4.4.2 Lessons Learned

Lessons learned regarding implementation of the Cost best practice are presented in Table 24:

Table 24: Cost Lessons Learned

#	Lesson Learned
1	Over time, organizations have approached cost modeling in a variety of ways, some with the contractor exercising total ownership over the model, others with the contractor and government each running independent models. A single model, jointly agreed upon, engenders a close teaming relationship. It also gives the government and the contractor a common baseline for evaluating yearly lot buys as well as potential design and programmatic changes. The contractor and the government should therefore jointly develop and maintain the PCM; both parties should agree on the overall architecture, ground rules, assumptions, level of detail, input sources/requirements, and outputs. Configuration control of joint PCM models need to be carefully preserved, with the program office and contractor agreeing on how changes to the model are to be approved and implemented.

Table 25: Cost Lessons Learned – Continued

#	Lesson Learned
2	Accurately modeling production costs during development can be difficult. Inputs to the PCM will initially rely on the limited fidelity of Rough Orders of Magnitude (ROM) and/or parametric estimates, so expect a sizeable amount of uncertainty associated with early PCM outputs. Do not allow this challenge to become an impediment, because the best prospects for system cost reduction occur during early program development phases. Over time, the PCM should be refined as the detailed design and associated manufacturing plans are developed. The PCM uncertainty level should gradually decline as design and process capabilities mature

5.4.5 Manufacturing Modeling and Simulation

An effective MM Program takes advantage of manufacturing M&S capabilities to assist in product design analysis and production planning. M&S can be used to identify potential production bottlenecks, evaluate cycle times and process variability, and determine necessary tooling, personnel, and inventory capacities. M&S initiates a series of inter-related, iterative activities intended to verify that production processes are given due consideration early, and throughout, the product development life cycle. SAE AS6500 requires M&S (this section), Manufacturing System Verification (MSV - Section 0), and Production Process Verification (PPV - Section 0) to verify that the production processes (including the associated infrastructure) will meet program cost, schedule, and quality requirements. These activities, performed throughout the development life cycle, ensure production process plans become progressively more mature (see Figure 5).

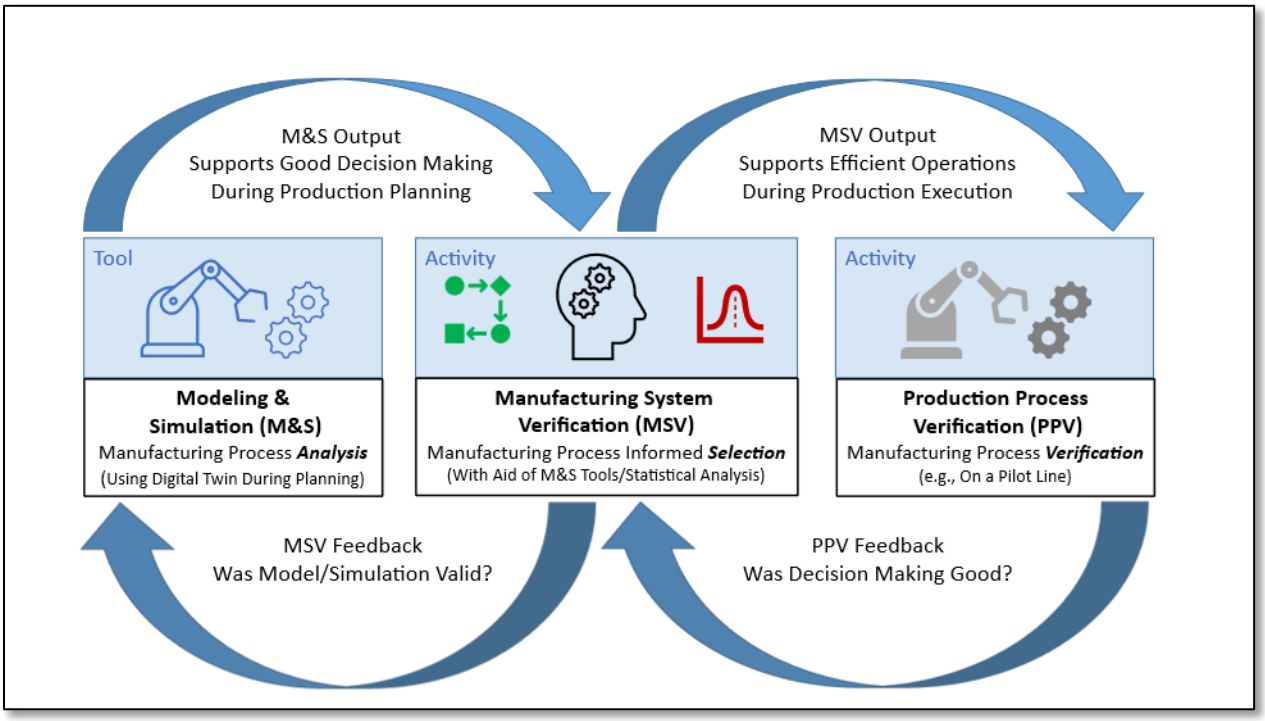


Figure 5: M&S, MSV, and PPV relationship

Of course, the scope and extent of these production process planning/verification activities should be tailored to match program scale and address program needs.

5.4.5.1 Guidance

Manufacturing M&S provides the capability to analyze, provide insight into, and optimize the properties and interactions among the materials, processes, tooling, facilities, and personnel involved in the design and manufacture of a new product; it does so in advance of final product designs and process decisions being baselined. The objective of M&S is to influence producibility and manufacturing resource decisions while beneficial changes can still be cost-effectively made.

Prior to the availability of effective M&S tools, traditional product development approaches often locked 65% to 75% of the cost to produce a product into the design baseline; opportunities to select more producible design alternatives have proven extremely difficult and/or costly to pursue once tooling has already been secured and production has already begun. Ideally, M&S tools are employed early in development and continue to be refined as the system design evolves, providing increased fidelity over time.

5.4.5.1.1 M&S support for product design

The product design process consists of repeated iterations of design-build-test-analyze cycles. Traditionally, the build phase of iterations included construction of physical mock-ups. While these physical mock-ups permitted visualization of the product and rehearsal of production build processes, they consumed significant resources (for example, time, money, floor space); the mock-ups could also be cumbersome and difficult to modify. Virtual M&S environments allow product design iterations to occur more quickly with significantly reduced investment in real resources (for example, time, money, floor space), thus providing greater, earlier insight into the effect of design changes at each stage. Stereolithography Apparatus (SLA) and Selective Laser Sintering (SLS) are legacy technologies that have long been rapid prototyping tools that provide sub-scale, and even full-scale, physical models. 3D Printing and Additive Manufacturing extend the same principles but include an increasing array of material options to produce not only models/prototypes but working production parts as well.

5.4.5.1.2 M&S support for risk management

Like line proofing, M&S supports risk management activities by verifying and validating production capabilities; unlike line proofing, M&S accomplishes this virtually. For example, Variation Simulation Analysis (VSA) tools are used to predict production yields by identifying sources of variation in production processes. By simulating the production of a large number of parts to a specified design tolerance given known production limitations, production yields can be predicted early in the design process, months before hardware is produced and assembled. In this way, designers can identify design-driven producibility limitations early in the development process, when it may be corrected at lower cost.

5.4.5.1.3 M&S support for production operations

The benefits of using M&S tools to support design activities spill over into subsequent production activities. Learning curve theory asserts manufacturing costs decrease over time due to ongoing improvements in production methods and experience gained by the workforce as they repeat assembly tasks. In theory, M&S can permit avoidance of early production unit inefficiencies by shifting some of the normally anticipated, early inefficiency back into an M&S virtual world, before producing the first physical unit. Notionally, virtual tools allow the producer to begin production of physical units at a point further down the learning curve, effectively avoiding much of the inefficiency common in early production units, as illustrated in Figure 6.

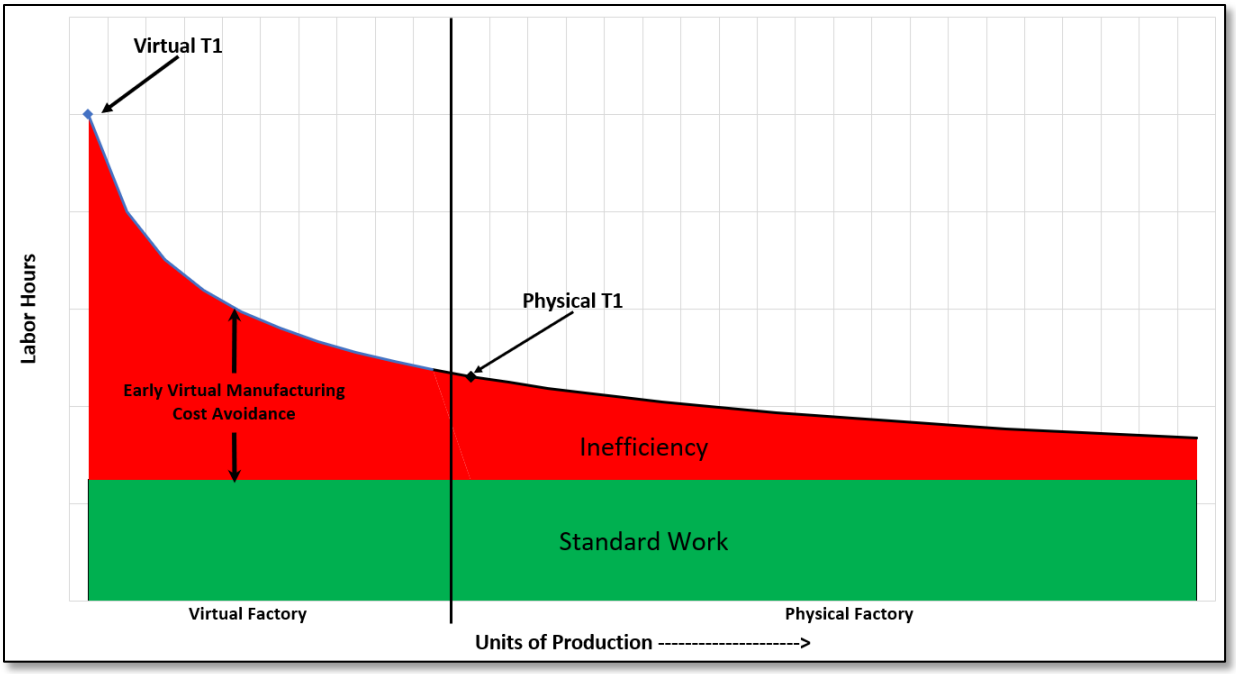


Figure 6: Early inefficiency cost avoidance in a virtual/physical factory environment

Furthermore, using an electronic product model with other simulation tools allows producers to extend M&S utility beyond supporting design activities to direct analysis and optimization of the factory production process. Discrete event simulation is a specific M&S tool used to model factory resources. The planned version of the factory (for example, floor layout, available human and machine resources) can be reproduced in a virtual environment and analyzed for capacity limits, machine/labor utilization, product movement routes/times, and other important production parameters. Factory design changes can be modeled and tested without making physical facility changes. Also, since transitions to new facility designs can take a significant amount of time, M&S can help validate progress along the way.

5.4.5.1.4 M&S support for broader digital engineering efforts

In the emerging digital engineering (DE) world, one important concept/enabler is the “digital twin”, which, according to MIL-HDBK-539, is a virtual replica of a physical entity that is synchronized across time. Digital twins exist to replicate configuration, performance, or history of a system; they allow product features and process performance to be studied and perfected prior to pouring a factory foundation, installing a CNC machine, fabricating a part, organizing a final assembly cell, or designing an assembly workstation. Because they are digital representations of actual parts and the facilities that produce them, these virtual models and simulations can increasingly be, and should be, integrated with CAD tools, manufacturing resource planning and scheduling tools, work instructions, and labor standards. Manufacturing M&S tools support a broader variety of manufacturing process analyses, including:

- **Yield modeling**: Focuses on predicting first pass yields based on key design and process attributes. Once a baseline process is established, process yields for new or changed designs can be predicted. This type of modeling is used extensively in the electronics fabrication industry.
- **Manufacturing ergonomics modeling**: Focuses on individual assembly processes; includes computer mock-ups of parts and processes to ensure human factors considerations are taken into account.

- **Production line modeling**: Focuses on material movement, processing times, and process yields (for example, scrap, rework and repair levels) to ensure production delivery rates can be achieved. Level of sophistication can vary from hand-drawn or stencil-based (for example, Microsoft® Visio®) value stream maps (elaborated upon below) to commercial discrete event simulations (for example, Java® based AnyLogic®, Simio®, Arena®).
- **Supply chain modeling**: Focuses on supplier delivery rates and inventory levels. More complex factors may also be considered, for example, supplier capabilities, capacities, and yields, learning curve effects, production disruptions, and obsolescence.
- **Value stream mapping**: Focuses on creation of a conceptual flow diagram which shows the process for creating a product from raw material through delivery to the customer. It should be complete with all types of information, material, parts, and physical processing times and physical movements as well as any queues that build into the system. Once the current state of the facility is accurately modeled, it's time for the team to go to work on evaluating where improvements can be made.

5.4.5.2 Lessons Learned

Lessons learned regarding implementation of the Manufacturing Modeling and Simulation best practice are presented in Table 26:

Table 26: Manufacturing Modeling and Simulation Lessons Learned

#	Lesson Learned
1	Modeling and simulation tools have been effectively used to analyze surge capability for individual factories specifically, and throughout the supply chain generally. The ability to assess manufacturing capabilities in a synthetic environment early in the design process has contributed to lower total costs, reduced technical and schedule risk in the transition to production, and increased confidence that programs can meet affordability targets. Specific examples of M&S benefits include: • One major commercial aircraft program reported a 90% reduction in design changes that would have normally occurred after the release of the product to the factory floor. • On a major aircraft program bulkhead, redesign cost was reduced by 27% and cycle time was reduced by 33% compared to other redesign activities that did not take advantage of M&S. • A major trainer aircraft tail stabilizer project that used solid modeling, parametric design, and M&S tools realized EMD savings of 28% compared to two other competitive redesign bids based on conventional design approaches. • A subcontractor was cleared of responsibility for delayed deliveries by a simulation that correctly identified prime contractor late deliveries of raw materials to the supplier as the root cause.

5.4.6 Manufacturing System Verification

An effective MM Program verifies that proposed production processes, tooling, and test equipment satisfy program requirements throughout development and production. M&S begins before and supports MSV, providing valuable data analysis and insight while MSV is itself a supporter of PPV (Figure 5). MSV involves assembling and analyzing available data regarding the statistical capability of candidate manufacturing process options, driving selection of those best able to produce conforming parts.

5.4.6.1 Guidance

MSV should be accomplished during the product development phase to determine if proposed/anticipated manufacturing processes (for example, using 3-dimensional modeling tools) and infrastructure (for example, using discrete event simulation tools) are sufficient to meet product specifications and production rate requirements. For large, complex parts, Modeling and Simulation may provide sufficient, cost-effective evidence to support an MSV.

M&S is not the only way to accomplish MSV; for production operations already in place, historical data and experience may be relied upon.

5.4.6.2 Lessons Learned

Following are lessons learned regarding implementation of the Manufacturing System Verification best practice are presented in Table 27:

Table 27: Manufacturing System Verification Lessons Learned

#	Lesson Learned
1	MSV is a continuous effort as the design matures and manufacturing methods evolve. Early analysis focuses on the capability of the various manufacturing methods. Once a manufacturing method is selected, a more detailed analysis can be performed to determine if it is meeting program requirements. Feedback at this point to engineering and management is critical as manufacturing methods may drive design changes (for example, tight tolerances that cannot be maintained, tighter tolerances required for high volume production). Alterations to the selected manufacturing method may also need to be considered. Regular and recurring communication is key during this process to assure that program requirements are met as manufacturing methods are selected and changes occur.

5.4.7 Manufacturing Workforce

An effective MM Program plans for, acquires, and develops a workforce to satisfy program requirements. Planning for the efficient organization and management of manufacturing workforce is crucial to success of the execution phase.

5.4.7.1 Guidance

As part of the MM Program planning process, contractors may discover and need to address manufacturing workforce gaps such as size, skills/capabilities, training, and certification. The contractor's anticipated workforce size and skills should be evaluated as part of MRL assessments and PRRs. Assess workforce capacity constraints to determine if skilled labor is available in sufficient quantities to meet program needs. Pay particular attention to skills requiring special training and/or certification. Investigate the ability of local training sources to produce anticipated needed skills, both formal (for example, university, community college, career centers) and informal (for example, on-the-job training).

5.4.7.2 Lessons Learned

Lessons learned regarding implementation of the Manufacturing Workforce best practice are presented in Table 28:

Table 28: Manufacturing Workforce Lessons Learned

#	Lesson Learned
1	When assessing the ability of the contractor to acquire skilled workers, consider local industries, competitiveness of the labor market, and availability of technical and higher education. Employee turnover is an effective indicator of workforce stability and employee morale.

5.4.8 Tooling/test equipment/facilities

An effective MM Program plans for, acquires, and develops tooling, test equipment, and facilities to satisfy program requirements.

5.4.8.1 Guidance

Tooling, test equipment, and facilities requirements should be carefully analyzed, planned, and validated.

5.4.8.1.1 Tooling/test equipment/facilities requirements analysis and planning

Tooling, test equipment, and facility requirements can be a major driver of cost and risk; they should therefore be considered during analysis of product design alternatives during the MSA phase. Facilities include the buildings and associated infrastructure (for example, physical and digital security, environmental controls, availability of utilities and necessary natural resources, etc.) needed to produce and store Work in Process (WIP) and finished goods. Tooling includes jigs, dies, fixtures, molds, patterns, taps, and gages; special tooling is the subset of tooling that is of such a specialized nature that without modification or alteration their use is limited to the development or production of particular supplies or parts. If new/unique tooling, test equipment, or facilities will be required, the contractor, and/or organic sustainment organization when applicable, should plan for its design, development, fabrication, qualification, maintenance, and use throughout all acquisition phases.

5.4.8.1.2 Tooling/test equipment/facilities validation

Once tooling, test equipment and facility requirements are established, product should be produced and demonstrated in a production representative or pilot line environment; rates and yields should be evaluated to ensure adequate capacity during production. Capacity analyses should consider both LRIP and FRP. Underlying rate and yield assumptions (for example, cycle times; scrap, rework, and repair rates) should be monitored during EMD and early LRIP and updated, if necessary. Preventive maintenance procedures should also be developed and verified at this time.

5.4.8.2 Lessons Learned

Lessons learned regarding implementation of the tooling/test equipment/facilities best practice are presented in Table 29:

Table 29: Tooling/Test Equipment/Facilities Lessons Learned

#	Lesson Learned
1	Special tooling should be serially managed using part numbers, serial numbers, unique item identifiers, and/or national stock numbers. Program managers should plan for the preservation and storage of special tooling; contracts and budgets should anticipate and accommodate methods of preservation and packaging, storage standards, storage location, and inspection requirements. Program managers should also, in collaboration with industry counterparts and the Defense Contract Management Agency (DCMA), establish an efficient process for dispositioning surplus and/or obsolete tooling and test equipment throughout the program lifecycle. In anticipation of the end of production, plans should: identify tooling and test equipment that will be necessary for ongoing operational/logistics support efforts, and ensure an orderly production line shutdown that, within budgetary constraints, (1) minimizes plant disruption, and (2) preserves flexibility to support post-production activities (for example, production line re-start, spares production).

5.4.9 Measurement System Analysis

An effective MM Program, at a minimum, performs Measurement System Analysis (MSA) to control variation on the measurement methods for KCs and CCs, and to identify the measurement process variation. Corrective actions are needed when MSA results fail to meet acceptance criteria.

5.4.9.1 Guidance

How do we develop confidence in the methods, validity, and scope of our sources of data used to make some of the most important decisions regarding production process effectiveness and efficiency? MSA attempts to answer this crucial question so that continuous improvement alternatives can be evaluated and promoted on the basis of justified belief rather than opinion.

5.4.9.1.1 MSA illustrated

Many realize by now that no two parts that come off a production line are exactly alike. What many have not as resolutely acquiesced to is the notion that measurement devices are themselves products that, at one time, came off a production line. If we extrapolate this understanding to the use of these devices to perform inspections and tests and supplement this knowledge with the additional understanding that there is often a human in the inspection and test loop, the importance of MSA also becomes abundantly clear. The challenge is illustrated using the very simple example shown in Figure 7. Notice not only does measuring precisely the same product yield different results, neither measurement result is actually correct. The variation between the results, as well as the variance in each result from reality, is not due to variation in the product; it is due to the variability (and a deficiency of needed precision) present in the measurement system. Add to this challenge the varying degrees of visual acuity that exists among inspectors, or even the varying degrees of visual acuity that exists in the same inspector at different points in time during the day, and the challenge becomes clear.

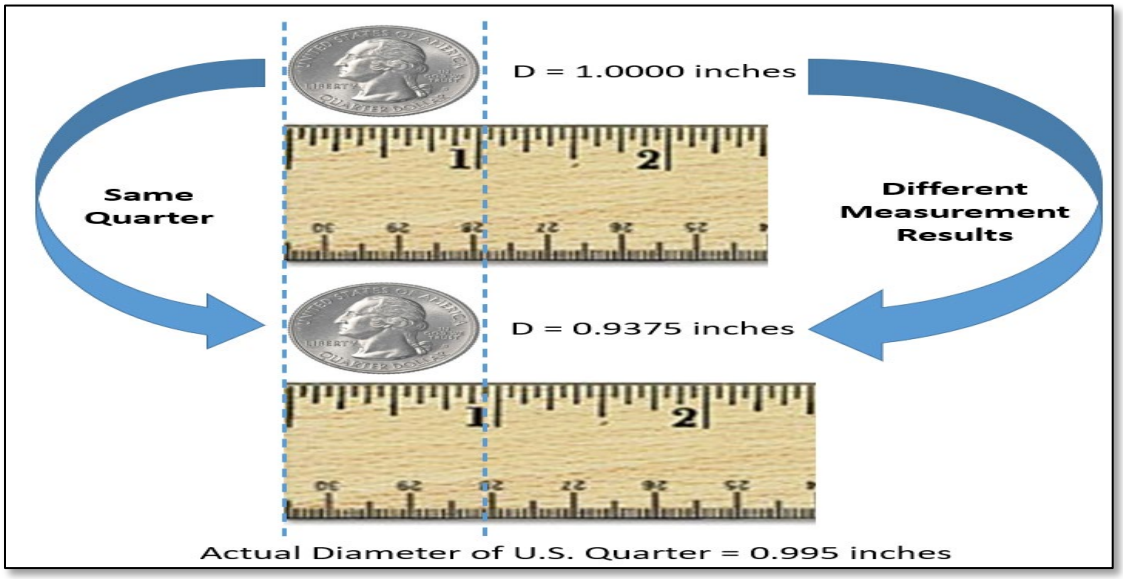


Figure 7: Why MSA is necessary

5.4.9.1.2 MSA Scope

MSA, then, is a formal statistical analysis that studies the extent to which the devices and people acting within a measurement system are reliably gathering data needed for decision-making. MSA recognizes that variability found in parts taken from a manufacturing process is not completely attributable to part variation itself; it can also be caused by variation in the measurement process. Calibration is an aid to increase measurement accuracy and reduce measurement variability, but it is not a complete solution to the measurement variability problem or, therefore, a substitute for MSA. This is because measurement system variability is introduced by a number of factors beyond the instrument used to perform the measurement and the person using the instrument, for example, changes in environmental conditions, variability in setup and measurement procedures, tooling and fixtures, and even software used in the measurement process. MSA, therefore, is an experimental and mathematical method of determining and accounting for all of the contributors to variation that exist *within a measurement process*.

5.4.9.1.3 MSA is more than calibration

Manufacturers should maintain an MSA program that includes but extends beyond calibration. An effective MSA quantifies all factors contributing to measurement error to ensure collected product measurement data is understood prior to making product or process change decisions. When measurement data being studied is continuous, the analysis is called Gage Repeatability and Reproducibility (Gage R&R); when data being studied is discrete, the analysis is called Attribute Agreement Analysis. During the conduct of an MSA, the following attributes of the measurement system should normally be assessed[13]:

1. **Repeatability:** This is the first “R” in “Gage R&R”. The measurement system is *repeatable* if the same person measuring the same object multiple times with the same device gets the same results.
2. **Reproducibility:** This is the second “R” in Gage R&R”. The measurement system is *reproducible* if multiple people measure the same object multiple times with the same device and all get the same results.
3. **Stability:** The measurement system is *stable* if its variation holds steady over time.
4. **Bias:** Bias is described as a one-directional tendency of the measurement system. For example, if a scale always seems to weigh higher than it should, this represents a bias. Bias can be adjusted for by altering the setting on (for example, “zeroing”) the scale.
5. **Linearity:** The measurement system holds steady over the entire continuum of desired measurements. For example, a scale should measure the weight of your pet mouse and your pet elephant with the same accuracy and precision.
6. **Discrimination or resolution:** The measurement system should be capable of producing values at a sufficient level of resolution to be meaningful. For example, does your scale only display pounds when you are routinely measuring the weight of items less than 16 ounces?

If any of these attributes are lacking, the data being collected loses its descriptive value. Measurement data will be untrustworthy, promoting a collection of false premises forming a shaky foundation for root cause/corrective action analysis and process improvement decision-making. MSA is the mitigator against the “garbage in, garbage out” aphorism; it is the tool of choice in this never-ending battle against the unknown unknowns.

[13] Source: isixsigma.com, Measurement System Analysis (MSA), https://www.isixsigma.com/dictionary/measurement-system-analysis-msa/, accessed September 25, 2022.

5.4.9.1.4 Additional MSA resources and guidelines

Gage R&R studies may be used for gages or instruments used to collect variable and attribute data to determine the measurement error, expressed as “Percent Gage R&R”. Following are Automotive Industry Action Group (AIAG) MSA Reference Manual Percent Gage R&R guidelines:

- <10%: the measurement system is considered to be adequate
- 10% - 30%: the measurement system may be acceptable depending on the application
- >30%: the measurement system is considered to be unacceptable.

SAE AS13003, “*Measurement Systems Analysis Requirements for the Aero Engine Supply Chain*”, is another source of MSA guidance for the Aerospace industry.

5.4.9.2 Lessons Learned

Lessons learned regarding implementation of the measurement system analysis best practice are presented in Table 30:

Table 30: Measurement System Analysis Lessons Learned

#	Lesson Learned
1	During the review of a contractor’s inspection processes for a Navy program, MSA issues were not realized until full production inspections were witnessed. After a part was machined a flatness test was performed at several locations on the part. In order to pass the flatness test the inspector had to apply pressure to the part until it passed. This process was not in the inspection procedure nor was there an indication on the amount of pressure or how to apply it. Questions were then raised on the repeatability and reproducibility of the inspection. To correct the issue a special fixture was created to aid inspection and the procedure was updated. Because engineering planners may easily demonstrate an inspection process in a controlled environment, an important aspect of conducting an MSA is to bring into view the human factor by witnessing first-hand inspections being performed by the intended work force in a production-representative environment. Companies without an MSA program may be missing quality issues concealed by measurement error. Without an understanding of MSA to aid decision-making, the assumption often defaults to parts passing inspection can be shipped. Absent a clear understanding of measurement error, it is possible for companies to ship non-conforming product even though the parts passed required inspections. Because there lingers a misconception that reliance on calibrated gages and instruments will suffice; MSA requirements are sometimes not fully implemented.
2	Efforts should be made to improve the measurement system when it is considered “unacceptable”. Nevertheless, the percentage ranges above are only guidelines; companies should decide what is appropriate for and consistent with their business strategy. If reasonable efforts to reduce Percent Gage R&R have been exhausted, a technique referred to as “Guard Banding” may be an option. Guard Banding is used to protect against incorrect conformity decisions caused by measurement uncertainty. Companies should be aware of the pros and cons of guard banding as it relates to “false acceptance” and “false rejection” (as described in ISO/IEC 17025:2017). Because both “false acceptance” and “false rejection” have negative consequences, there is a tradeoff associated with reducing the risk of false acceptance: artificially inflating the scrap rate.

5.5 Manufacturing operations management

There are nine MM Program requirements associated with Manufacturing Operations Management: (1) Production Scheduling and Control, (2) Manufacturing Surveillance, (3) Continuous Improvement, (4) Variability Reduction (VR), (5) Process Capabilities, (6) Production Process Verification (PPV), (7) First Article Inspections (FAIs)/First Article Tests (FATs), (8) Supplier Management, and (9) Supplier Quality. Each of these requirements will be addressed in the following subparagraphs in turn.

5.5.1 Production scheduling and control

An effective MM Program establishes and maintains an effective production scheduling and control system. The production scheduling and control system determines production lead times, schedules production activities to meet production milestones and goals, tracks components and assemblies through the production process, ensures configuration changes are properly addressed on the production floor, and manages customer-owned material/equipment.

5.5.1.1 Guidance

Knowledge of production capability, capacity, and constraints and the nature of customer demand is essential for efficiently managing production operations. An advanced QMS is always a good companion, whether operating a forecast-based PMS with push-initiated controls or a customer demand-based PMS with pull-initiated controls. However, recognize that a PMS employing production planning and control systems based on lean principles *requires* an advanced QMS founded on defect prevention principles; in other words, a defect prevention culture would be necessary even if the MM Program did not otherwise require it.

5.5.1.1.1 Production scheduling approaches

There are essentially two schools of thought regarding production scheduling: (1) schedule according to forecasts/predicted demand or (2) schedule according to actual customer demand. The difference is important because it influences the selection of production control mechanisms used to manage movement of material on and through the shop floor. Forecasts, even those based on historical demand trends, drive production in anticipation of need; they therefore cause production to be pushed through a manufacturing system. Customer demand, on the other hand, triggers production after a bonified need has been identified; it causes production to be pulled through a manufacturing system. Therefore, ability to accurately anticipate customer demand, more than any other factor, drives the selection of the best method of production scheduling and control. A more thorough treatment of production scheduling and control methods is provided in Appendix C.

5.5.1.1.2 Assessing a contractor's production scheduling and control effectiveness

To obtain insight into the effectiveness of a contractor's production control system, program offices and their delegated administrative contracting offices may request access to the contractor's production scheduling and control system (ideally) or to metrics generated by the system (minimally). Since DoD contractors employing lean production planning and control systems typically conclude with a balanced, takt-driven, final assembly line, the program office may wish to require a Line of Balance (LOB) metric to track build progress and predict future delivery performance. According to The Defense Systems Management College (DSMC) in their *Scheduling Guide for Program Managers* (October 2001)[14], "*The LOB represents the number of units that should have passed through each control point (cumulatively) to satisfy the contract delivery schedule."* The guide provides step-by-step instructions for producing LOB metrics, and presents a sample completed LOB shown in Figure 8.

[14] The guide may be found at this link: Scheduling Guide for Program Managers (acqnotes.com); (https://www.acqnotes.com/Attachments/Scheduling%20Guide%20for%20Program%20Managers%20Oct%202001.pdf)

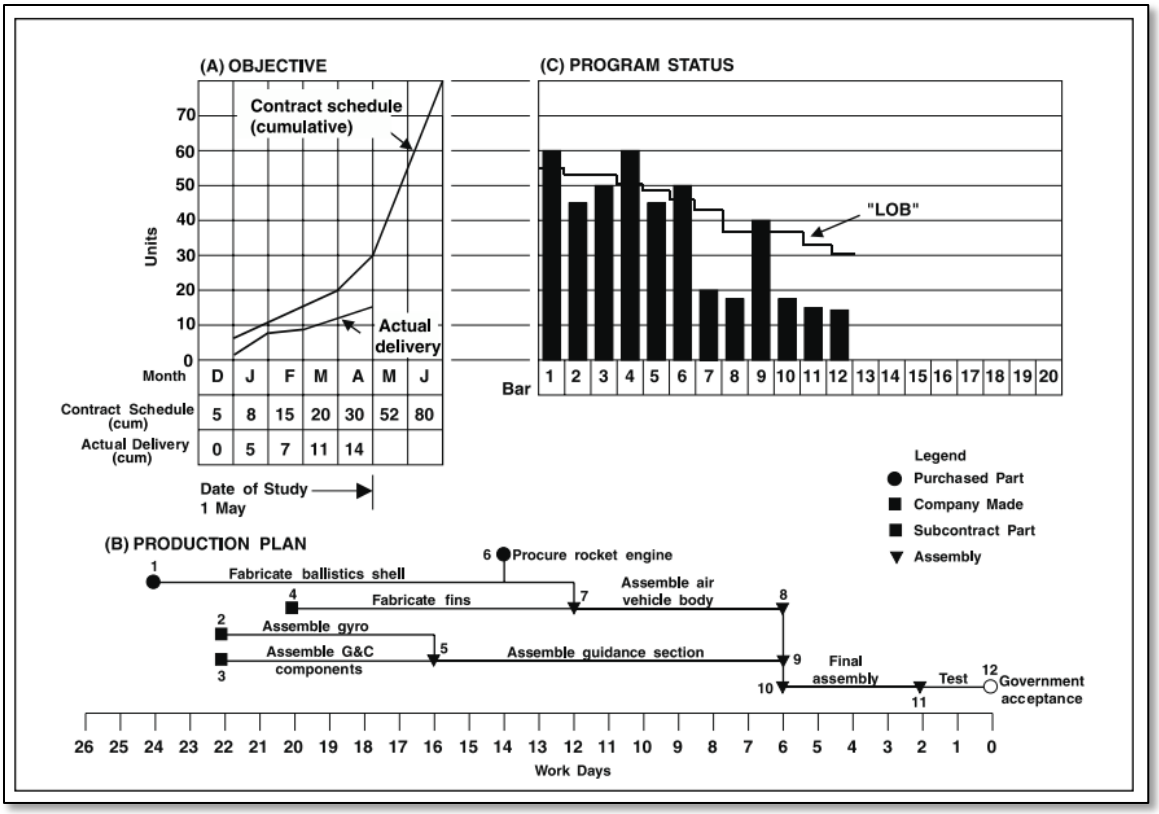


Figure 8: Sample Line of Balance (Source: DSMC, 2001)

5.5.1.1.3 The power of Line Of Balance

The power of this representation comes from its simplicity; the program status chart in the upper right corner of Figure 8 displays the status of the production line at a glance. Each bar that deviates from the LOB line indicates the number of units behind or ahead of schedule the production system is at that production control point. WIP is building up at control points 1, 4, 6, and 7 while the remaining control points are lagging behind the production plan. This example makes it clear that the production line is not lean because kanban control and takt-based production line pacing would not permit this to happen (for example, for work to proceed in such an uneven manner). When lean operations are in place (that is, paced using “takt time production control), another metric is often used to describe the health of the production scheduling and control system, often described as “travelled jobs”. This metric identifies any work that has been passed to a downstream operation to be completed “out of station”. The objective, of course, in a lean production environment, is for the number of travelled jobs to be zero. Tracking the number of travelled jobs toward this goal is viewed as an indicator of process maturity.

5.5.1.2 Lessons Learned

Lessons learned regarding implementation of the production scheduling and control best practice are presented in Table 31:

Table 31: Production Scheduling and Control Lessons Learned

#	Lesson Learned
1	The appropriate production scheduling and control approach to use depends on the nature of the product being produced and the ability of its demand to be predicted or controlled: Push-based production scheduling and control systems based on forecasts rather than actual customer demand struggle to accurately predict and/or adequately manage capacity limitations/bottlenecks in production lines. This often leads to overproduction at non-pacing operations which creates undesirable, capital-hogging build-ups of WIP. Pull systems rely on predictable or controllable customer demand to initiate and drive production. As such, pull systems are at a disadvantage when customers expect their demand for a product to be satisfied sooner than the lead time required to pull the product through the production system.
2	Some consider forcing selection of a push vs. pull production scheduling and control system a false dilemma; those not firmly entrenched in one camp or the other suggest the answer need not be either/or, but can be both/and. M&Q SMEs should evaluate whether claims that both systems can coexist on the same production line with a clear understanding how the methods, benefits, and drawbacks of each approach might be influenced by the nature of the production systems product mix and the predictability of customer demand. It is possible that the both/and approach could be reasonable if, for example, a contractor elects to combine push-based scheduling and control in early “fabrication” work centers with pull-based scheduling and control where all the parts come together in subassembly/assembly operations.

5.5.2 Manufacturing Surveillance

An effective MM Program establishes, collects, and maintains metrics that provide insight into production efficiency/effectiveness and product quality. Before beginning a discussion of manufacturing surveillance, which requires establishment, collection, and maintenance of metrics, it is perhaps best to take a moment and define terms. While there are many definitions of the term offered, the following definition for “metric” adequately suits the purpose: *“A metric is a measurement, taken over time, that communicates vital information about a process or activity. A metric should drive appropriate action. Metrics must be linked to strategic planning.”* Note the four essential characteristics emphasized in this definition: (1) taken over time (displays a trend), (2) communicates vital information, (3) drives appropriate action, and (4) linked to strategic planning. Appendix A describes the essence of manufacturing management program strategic planning as: (1) make the right thing, and (2) make the thing right. Make the right thing encompasses all the producibility and production planning activities tracked through development using MRL assessments at multiple technical review checkpoints. Once production begins, manufacturing surveillance becomes the control engine for the Execution goals presented in Appendix A which are reproduced here:

1. Execute Processes Effectively: Measure and manage process capability to ensure it is producing customer-satisfying product at highest desirable level of quality.
2. Execute Processes Efficiently: Measure and manage process capacity to take optimal advantage of available, capable manufacturing processes.

Common surveillance methods to monitor and evaluate the effectiveness (that is, Cost of Quality (COQ) methods) and efficiency (for example, Work Measurement and Learning/Improvement Curve Theory) of contractor execution are presented in Appendix D.

5.5.2.1 Guidance

Contractor submission of factory performance data should be expressed as a contractual requirement. Examples of helpful factory performance data include:

- Summary Production Schedule
- Line of Balance (or similar) production status charts (see Section 5.5.1.1)
- Supplier schedules and status (see Section 0)
- Labor performance data (actual hours versus work measurement standards)
- COQ (which includes, but is not limited to, Scrap, Rework and Repair metrics)

Without factory performance data, the program office is unable to independently validate a contractor's ability to achieve a contract delivery schedule, respond to "What-If" scenarios, or judiciously assess contractor planned recovery schedules. When factory performance data is required formally by a Contract Data Requirements List (CDRL), consider accepting the data in contractor format to avoid any added expense incurred by the contractor to reformat the data. In the absence of formal contract factory performance data delivery requirements, the government and contractor team should develop an agreement on what data will be provided to enable manufacturing surveillance; some contractors willingly provide customer access to surveillance data and metrics electronically.

5.5.2.1.1 Labor performance surveillance

Learning theory is one powerful process efficiency surveillance tool. The very essence of learning theory is that manufacturing efficiency improves naturally unless impeded. Learning theory recognizes a variety of legitimate impediments that may be introduced (for example, design changes, end of production); however, experience demonstrates there are also less legitimate ones. One opponent to learning theory is Parkinson's Law. When appropriate motivators fail to exist, Parkinson's Law can stealthily stall or even counteract efficiency gains that would have otherwise been naturally realized by the passage of time. It can even frustrate active process improvement efforts[15]. Learning theory concepts are addressed in greater detail in Appendix A.

5.5.2.1.2 Cost of Quality surveillance

COQ is one powerful process effectiveness surveillance tool. Discovering the true CoQ is not easy. Government program office quality managers may encounter pushback from industry when CoQ data is requested. Furthermore, a contractor's systems and methods for collecting the various elements of CoQ may not be sufficiently mature at the start of a program. While it might be desirable to identify all three categories of quality costs (appraisal, prevention, and failure) at the defect level, it may not be possible at first. Collecting failure costs at the defect level and aggregating appraisal and prevention costs at a cumulative level is a good place to start. Of course, if CoQ data collection and reporting is not in the contract, it likely will not get done; contractor collection and government access to CoQ information is enabled by the inclusion of contract language requiring the identification and segregation of CoQ. COQ concepts are addressed in greater detail in Appendix D.

5.5.2.1.3 Coordinating surveillance with other federal agencies

Manufacturing surveillance may be accomplished at contractors producing DoD systems and parts by other federal agencies. For example, commercial (and the commercial components of commercial derivative) aircraft fall under the authority of FAA certification process. Aerospace

[15] This phenomenon, which he dubbed "Parkinson's Premium", was first observed repeatedly occurring in numerous contractor and government production and repair environments and documented by Waring "Bubba" Worsham, Manufacturing Systems Engineer, in November, 2011.

contractors may seek and be granted FAA Production Certificates (PC) by demonstrating compliance with 14 CFR part 21, subpart G, “Production Certificates”. This regulation states that a “holder of a production certificate must establish and describe in writing a quality system that ensures that each product and article conforms to its approved design and is in a condition for safe operation.” It is important to understand how the surveillance role of other federal agencies differs from the expectations of DoD programs. For example, FAA surveillance focuses only on manufacturing effectiveness. The FAA is responsible for ensuring quality and airworthiness of aircraft purchased under their certificates. Unlike DoD programs, the FAA has no interest in the rate at which aircraft are produced or the price at which aircraft are sold. Therefore, insight into manufacturing efficiency will need to be addressed in the contract SOW and in the Memorandum of Agreement (MOA) with the cognizant DCMA. Department of the Army Regulation 770-3, “*Type Classification and Material Release*”, describes a type classification process that ensures materiel, including commercially available materiel, is acceptable for Army use prior to procurement. It also describes a materiel release process that ensures procured materiel is safe, suitable, and supportable. The quality manager needs to determine the extent to which other federal agency QMS oversight meets the needs of the DoD, where gaps may exist, and how to address those gaps.

5.5.2.2 Lessons Learned

Lessons learned regarding implementation of the manufacturing surveillance best practice are presented in Table 32:

Table 32: Manufacturing Surveillance Lessons Learned

#	Lesson Learned
1	One major aircraft contractor very successfully instituted customer satisfaction data gathering, analysis, and improvement program that involved customer surveys upon aircraft delivery, followed by another at first maintenance check. The program was designed and used to communicate newly delivered aircraft quality escapes discovered by end-users back to the production floor to prevent future occurrences. Customer satisfaction and aircraft performance data was captured during delivery flight through first home station check, which is a period of approximately six months. A contractor quality manager proceeded to the receiving flightline prior to the aircraft arriving; program office M&Q SMEs were also invited and frequently elected to participate. Early customer satisfaction results were disappointing, but over time and with persistence customer satisfaction scores improved dramatically. Eventually, customer satisfaction scores routinely reflected “very good” to “excellent” and zero write-ups on ferry flights became routine. The success of this program and the data it collected/reported became supporting rationale for Contractor Performance Assessment Reporting System (CPARS) ratings and contract award fees.

5.5.3 Continuous Improvement

An effective MM Program maintains a continuous improvement program that targets opportunities for improvement in quality, delivery, performance, and cost.

5.5.3.1 Guidance

Validation of continuous improvement results regarding manufacturing processes is not subjective; statistical methods have been developed to describe, with defined measures of confidence, whether improvement has actually occurred as a result of a manufacturing process improvement initiative. Continuous improvement applies to both statistical measures of effectiveness and efficiency. Recall that effectiveness expresses the ability of the process to produce customer satisfying product, efficiency expresses the ability of the process to do so routinely at minimum necessary cost. Refer to Appendix E for a more thorough treatment of continuous improvement concepts, including examples of how to pursue (1) continuous effectiveness improvements and (2) continuous efficiency improvements.

5.5.3.2 Lessons Learned

Lessons learned regarding implementation of the continuous improvement best practice are presented in Table 33.

Table 33: Continuous Improvement Lessons Learned

#	Lesson Learned
1	Innovative contractual incentives may be required to encourage contractors to embrace the long-term benefits of continuous process effectiveness and efficiency improvement. Award fees tied to product performance objectives over threshold, incentive fees tied to cost reductions below target and even funded Contract Line Item Numbers (CLINs) dedicated to efficiency projects have been used on some programs.
2	One large aircraft acquisition program office and its contractor embarked on a period of significant investment in “affordability projects” specifically aimed at reducing the cost of the aircraft. The desired result, from an improvement perspective, was to move the learning curve away from the program’s “historical” path, to shift it down and/or steepen its slope. While this was programmatically desirable, and evidence suggested it was markedly successful, it introduced complexity into the analysis necessary for labor projection. If the intent and result of the affordability projects was to change the course of history, projection from history needed to be fine-tuned to account for it. Program office and contractor analysts therefore developed an approach to account for the effects of this infusion of affordability projects on the historical/measured learning curve. Analytical assumptions were made concerning how much these projects might impact the curve in a downward direction. As time passed between lots and performance data was captured, the true effect of the affordability projects became available for review and incorporation into the model’s assumptions. Another tweaking technique was developed to perfect future lot estimates by adjusting the lot’s learning curve take-off point based on measured recent reality. All of this fine-tuning was designed to clear the murkiness in the learning curve crystal ball created by atypical, albeit desirable, conditions.
3	Even when data is trustworthy (see 0), it is not always relied upon to support prioritization and selection of continuous improvement projects. Unfortunately, it seems, the “check” step in Shewhart’s cycle does not always drive the “act” step. This phenomenon was discovered playing out during an evaluation of an ALC quality system. Even though large quantities of process measurement data were being collected, and there were a large number of process improvement efforts ongoing, there was not always a clear path from the data being collected to the selection of projects being pursued. When evaluating continuous improvement programs, make sure the path from quality issue detection to continuous improvement project is clear; closed-loop confirmation of the improvement project’s positive net effect is not possible otherwise.

5.5.4 Variability reduction

An effective MM Program maintains a Variability Reduction (VR) program focused on achieving stable and capable processes. A VR program will accomplish this by collecting and analyzing data that identifies and isolates manufacturing process variation and implementing effective process variation controls.

5.5.4.1 Guidance

VR, as a concept, maintains grading a process on its ability to produce product features within specification limits (an assessment approach known as “goal-posting”) is an inadequate measure of process capability. VR recognizes, as Genichi Taguchi famously asserted, that there is a loss of product value associated with any deviation from nominal even when the deviation falls within the specification limits (see detailed discussion in Appendix B). Value loss may come in the form of performance degradations and/or increases in life cycle costs. Because larger deviation from nominal yields greater loss, the objective of VR is to reduce process variation from the specified nominal value. Variability reduction programs should minimally focus on product key and critical characteristics (see Section 0). The relationship between inherent process variability vs. specified product design limits is therefore

considered a truer, more comprehensive measure of a process's ability to produce quality product (see discussion of Process Capability in Section 0). Once this ratio of process variability to specification limits has been quantified for each key process, it can be used to quantitatively and systematically prioritize VR opportunities.

5.5.4.1.1 VR efforts during development

The following VR efforts, accomplished during development, lay the foundation for continuous quality improvement during the production phase:

- Develop control plans for critical processes
- Begin data collection on key processes to determine process capabilities
- Provide measured process capability feedback to designers
- Implement improvements in design standards and/or the design process
- Implement improvements in manufacturing processes

As developmental units are produced, increasingly relevant and reliable process data becomes available that provides greater insight into the true capabilities of planned processes. This authentic process capability experience should be fed back to the design engineers, thereby informing ongoing and future design decisions.

5.5.4.1.2 VR efforts during production

VR efforts continue into the production phase; however, the focus shifts to verifying critical process capability and addressing shortfalls with special variability reduction efforts. Specific VR activities during production include:

- Monitor process performance data
  - Initiate preventive actions to address special causes of variation
  - Initiate process improvements to reduce common causes of variation
- Analyze field reliability data
  - Assess user feedback (that is, from end users and product support personnel)
  - Enhance product design to improve producibility

VR benefits to producers include cost savings due to, for example, reduced redesign efforts, reduced fabrication and assembly hours, reduced scrap, rework, and repair rates, and reduced reliance on end-item inspections to detect and correct nonconformance. Customer satisfaction is positively impacted as well due to improved product fit, performance, and reliability/service life.

5.5.4.1.3 VR Process

Figure 9 presents a typical sequence of activities for an effective VR Program; the paragraphs following the diagram explain each step in this variability reduction process in turn. One method of requiring VR contractually is to include SAE AS9103 in the contract SOW. Ultimately, while VR program details may vary somewhat from the precise steps outlined below, each should have in common the aggressive pursuit of CoQ reductions through continuous process improvement.

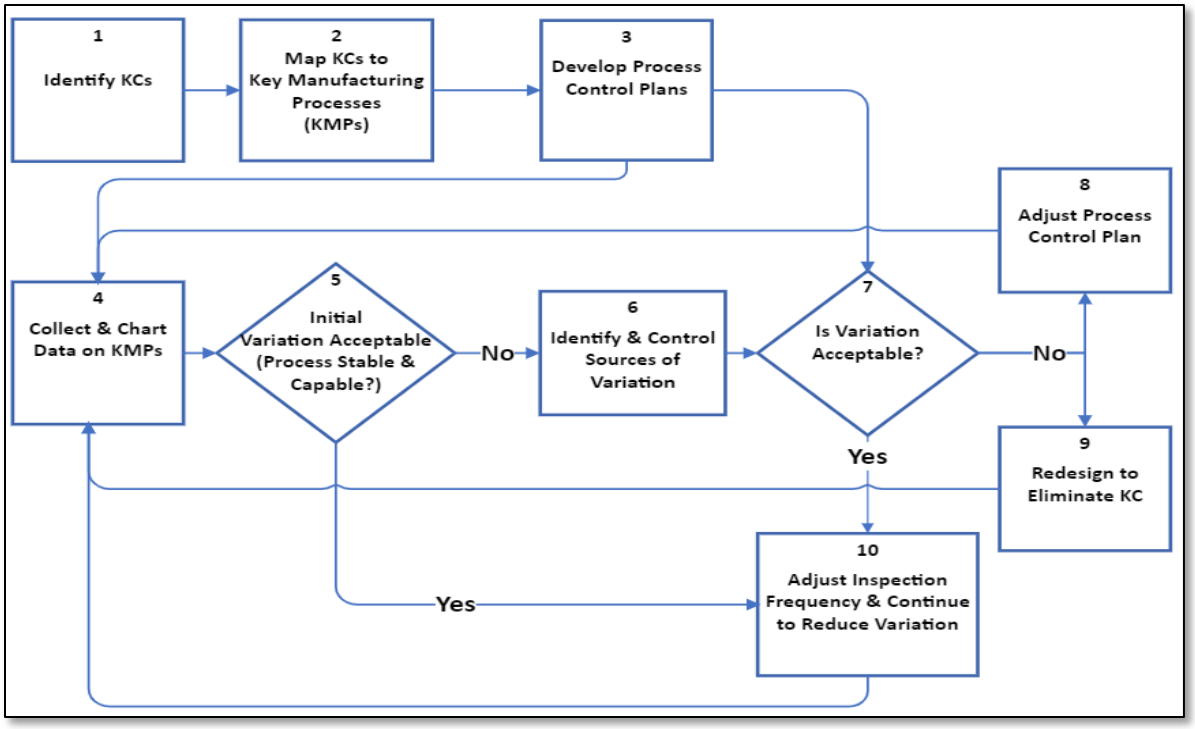


Figure 9: Variability reduction approach

5.5.4.1.3.1 Identify KCs

Refer to Section 0 for details on key characteristic identification.

5.5.4.1.3.2 Map KCs to KMPs

Many successful VR activities begin with process flowcharting, resulting in detailed analyses of inputs, outputs, controls, and enablers for each process step. The flowchart, and the detailed data associated with it, serves as a helpful starting point for tracing KCs to the KMPs that will produce them.

5.5.4.1.3.3 Develop Process Control Plans

For each KMP, the contractor should develop documented plans to control KC variation. Process control plans should minimally ensure only product within specification limits is accepted (that is, special causes detected and addressed, even if this means 100% inspection), and as a goal, pursue analysis and elimination of special causes and reductions in common causes of process variability. Since a single process may be responsible for producing more than one key characteristic, a single process plan may address multiple KCs. The content of the plan and its update depends on the complexity of the characteristic and the nature of the process producing it. The control plan should minimally include a brief explanation of the KC, the data that will be collected, how and where in the process it will be collected, and how the data will be analyzed (for example, type of charting and who is responsible for analyzing it). SPC techniques are not required for every KC but are highly encouraged when data is available and sufficient to warrant it. Process control plans should also address the measurement system and its ability to accurately ensure product conformance to specifications (see Section 0).

5.5.4.1.3.4 Collect and analyze Key Manufacturing Process performance data

Collect data in accordance with the process control plan. Early in development when few items are produced, short-run statistical techniques may be necessary. Alternatively, it may be possible to exploit data from other products that were produced using the same process.

5.5.4.1.3.5 Assess initial variation acceptability

To evaluate acceptability, calculate the process capability index (Cpk) (see Section 0). SAE AS9103, “Aerospace Series – Quality Management Systems – Variation Management of Key Characteristics”, requires processes to be statistically stable and capable (that is, with Cpk > 1.33 or as otherwise agreed by the customer).

5.5.4.1.3.6 Identify and control sources of variation

Both special and common causes of variation (described in Appendix E) need to be addressed. Special causes need to first be isolated to determine the true expected output of the process; root cause analysis of “outliers” should be performed, and controls should be put in place to minimize their occurrence. Common cause variation should then be targeted for control; because of its inherent nature, common cause variation can only be reduced by making fundamental changes to the process or its environment (for example, installing devices that reduce the effect of high humidity on process output).

5.5.4.1.3.7 Assess variation acceptability

If process variation has decreased to an acceptable level, make appropriate adjustments to inspection frequency and continue improvements efforts as long as they rare yielding a desirable return on investment. If process variation remains unacceptable after special causes have been eliminated and common causes controlled to the extent possible, other actions may be necessary. If it is not economically feasible to further reduce variation by changing the production process, product redesign and process control plan adjustments remain options to pursue.

5.5.4.1.3.8 Adjust Process Control Plan

Process control plans should be updated to account for changes (whether they be implemented improvements or observed decrements) in process capability whenever they occur.

5.5.4.1.3.9 Redesign to eliminate KC

When processes are not available to reliably produce a specified design, a product redesign to eliminate the key characteristic should be considered as an alternative to implementing process controls on an incapable process.

5.5.4.1.3.10 Adjust inspection frequency and continue to reduce variation

If process variation can be limited to a range of acceptability, product inspections may be reduced. Certified operators may rely on SPC techniques to ensure process shifts do not occur unnoticed, and the quality organization may audit the SPC data collection process and/or sample the final product to ensure the process control plans remain effective.

5.5.4.2 Lessons learned

Lessons learned regarding implementation of the variability reduction best practice are presented in Table 34.

Table 34: Variability Reduction Lessons Learned

#	Lesson Learned
1	It is important to maintain focus on the relationship between processes capabilities and product features. Focusing too much on product features alone can drive a predisposition toward analyzing data on a part number by part number basis, losing sight of the beneficial aggregate knowledge gained by acknowledging KCs of different parts may have been produced by the same process. At times, especially in low-volume production environments, it may be possible to achieve process capability statistical significance when considering aggregate quantities of similar features.

Table 35: Variability Reduction Lessons Learned – Continued

#	Lesson Learned
2	Distilling large quantities of raw data into simple, understandable metrics can be challenging. Still, statistical data collection need not be tedious or time-consuming; statistical analysis of production data has been facilitated by many automated devices developed in recent years (for example, gauges capable of collecting inspection data and performing statistical calculations). It is important that M&Q SMEs maintain proficiency in the range of statistical methods used to evaluate production floor data since even appropriately distilled and presented VR metrics can be misinterpreted by those unfamiliar with the fine art of statistical interpretation.
3	While many SPC techniques require substantial quantities of data to achieve desired confidence, SPC tools for small production runs do exist. But even small production runs may offer the opportunity to collect adequate, statistically significant quantities of data when viewed a bit more abstractly. Some product builds consist of processes repeated hundreds or thousands of times (for example, hole drilling), lending themselves to large-batch SPC analysis. In addition, large quantities of inspection data repetitions may be gathered by taking multiple measurements from a single part (for example, deviations from nominal of an outer mold line on a machined part).

5.5.5 Process capabilities

An effective MM Program uses statistical tools to analyze process capabilities and minimize process variability.

5.5.5.1 Guidance

Process capability indices should be identified, implemented, and tracked for KMPs and CMPs, when statistically significant data is available. The process capability information should be made available to design engineers to influence design decisions. Process capability improvement efforts should consider competing impacts on producibility, quality, and cost.

5.5.5.1.1 Measuring and calculating process capability

Product *specification limits* (that is, tolerances) reflect what is required by the design. Process *control limits*, derived from inherent process variability and therefore the object of VR efforts in Section 0, simply reflect expectations regarding a process's ability to produce product features within specified limits. When process control limits (what is expected of the process) are compared to product design feature tolerances (what is required of the product), the resultant statistic represents how good a match the two are. The mathematical ratio is called process capability and is represented as "C_p". It is calculated as follows:

$$C_p = \frac{USL - LSL}{6\sigma}$$

Where:

σ = Process Standard Deviation

USL = Upper Specification Limit

LSL = Lower Specification Limit

Process capability, therefore, is a mathematically calculated measure of process goodness which reflects historical, and can be used to predict, future process yields. It serves as a meaningful benchmark for process trade studies and continuous improvement efforts. When process centeredness cannot be assumed, the process capability statistic is modified to describe the measure of capability in terms of the worst-case scenario (for example, the shortest distance from the uncentered process to the nearest control limit) and is represented as

C_{pk}[16]. C_{pk} is calculated as follows:

$$C_{pk} = \text{Minimum}\left(\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right)$$

Where:

μ = Process Mean

σ = Process Standard Deviation

USL = Upper Specification Limit

LSL = Lower Specification Limit

5.5.5.1.2 Interpreting process capability

For simplification, the C_{pk} calculations shown above, and the C_{pk} guidance provided below assume the most common circumstance: the product's design characteristic has an optimum value with specification limits on either side of optimum (for example, the item must be 12 inches long, plus or minus one inch)[17].

5.5.5.1.2.1 A capable process, illustrated

When the process +3σ control limits (that is, Upper Control Limit (UCL) – Lower Control Limit (LCL)) match the design-specified tolerance range (that is, USL – LSL), the process is said to be "capable" with $C_{pk} = 1$[18]. This means that the process will produce conforming product 99.97% of the time as depicted in Figure 10 (that is, the area under the standard normal curve between -3σ (LCL) and +3σ (UCL) is 0.9997). Three out of every 1,000 parts will be nonconforming, on average, if produced using a process with a $C_{pk} = 1$.

[16] For processes with tolerances expressed as plus or minus a specified value, calculation of C_{pk} will always produce the same result that C_p produces for centered processes; C_{pk} is therefore the preferred way to express process capability generally. C_{pk} is always a true measure of expected process capability, C_p is only true if the process also happens to be centered.

[17] The discussion within this handbook is limited to cases involving two-sided tolerances (perhaps the most common) in order to illustrate the concept of process capability. For cases involving other scenarios (for example, a one-sided tolerance specified for a bearing in which there is a maximum allowable deviation from the optimal out-of-roundness of 0.0), please consult statistical references/experts for more detailed information.

[18] This is an academic, definitional statement, not a policy one. Some producers establish higher targets, and therefore harbor a different assessment of what "capable" means (for example, some manufacturers target a minimum $C_pk \geq 1.33$; others may pursue the true 6σ approach and target $C_{pk} \geq 2.0$).

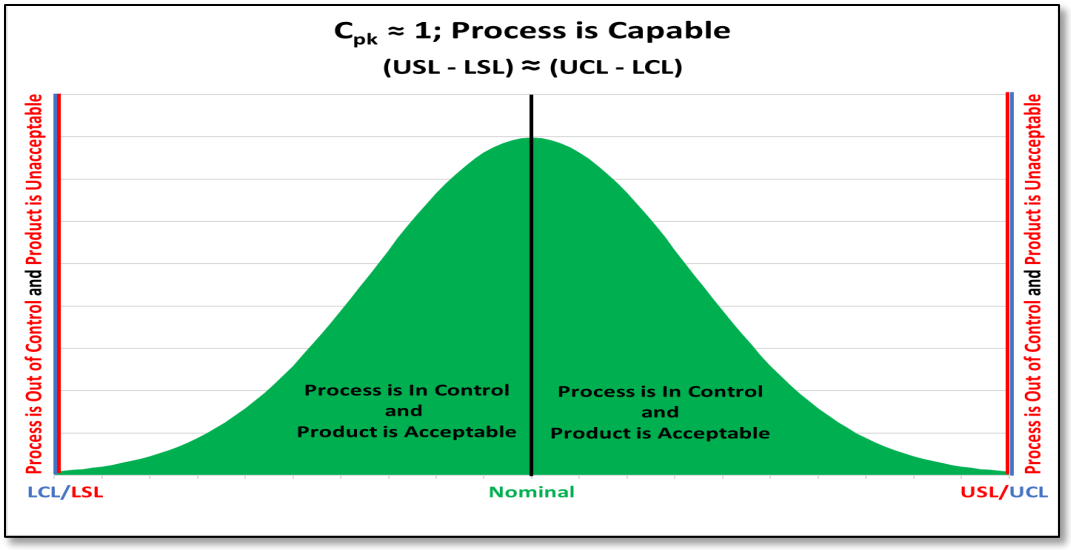


Figure 10: Capable process illustrated

5.5.5.1.2.2 A more than capable process, illustrated

Processes with measured $C_{pk} > 1$ are more than capable. This means that the process will produce conforming product more than 99.97% of the time (see Figure 11), which translates to fewer than three defects per thousand.

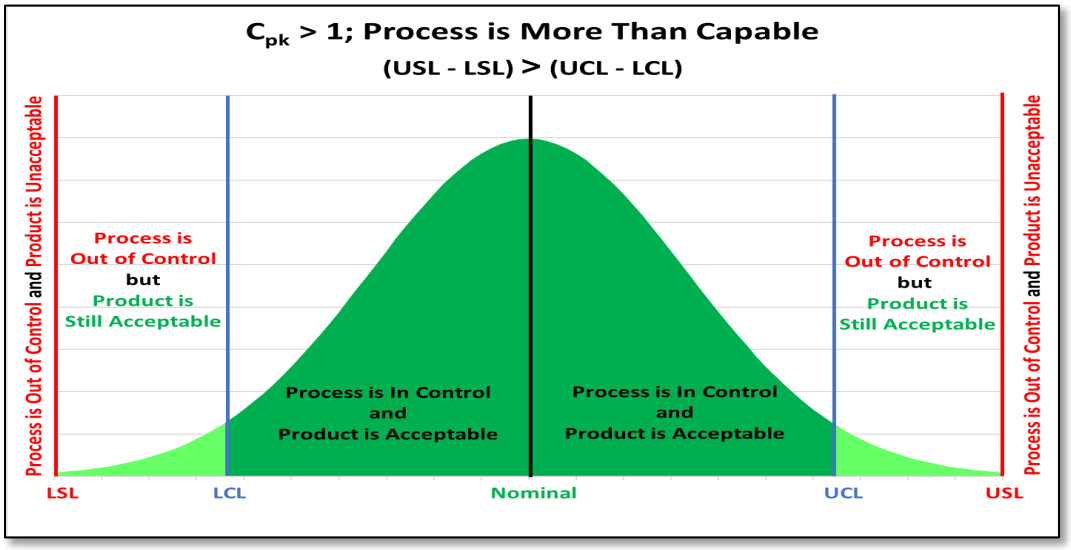


Figure 11: More than capable process illustrated

5.5.5.1.2.3 A less than capable process, illustrated

Processes with measured $C_{pk} < 1$ are less than capable. This means that the process will produce conforming product less than 99.97% of the time (see Figure 12), which translates to more than three defects per thousand.

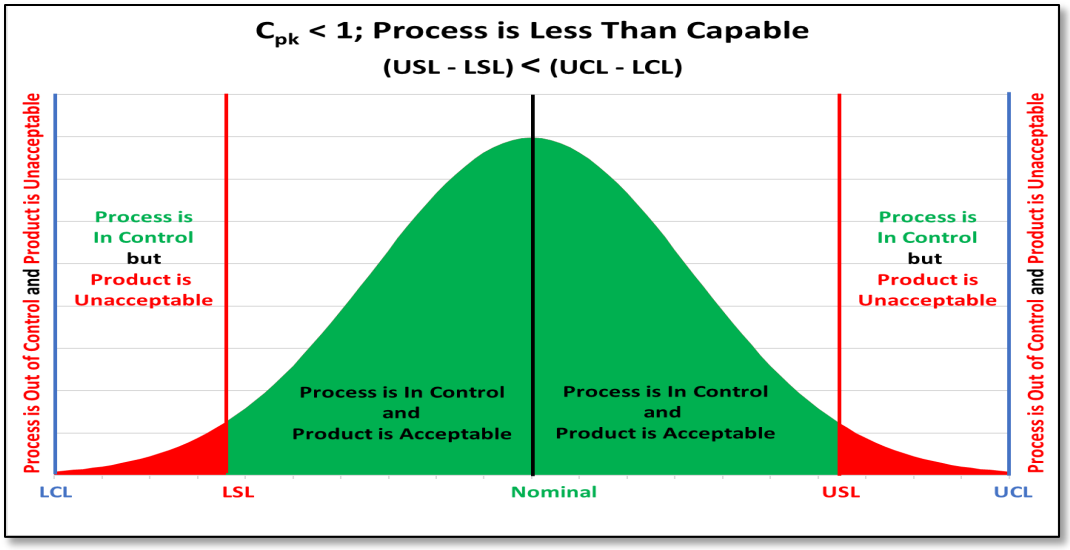
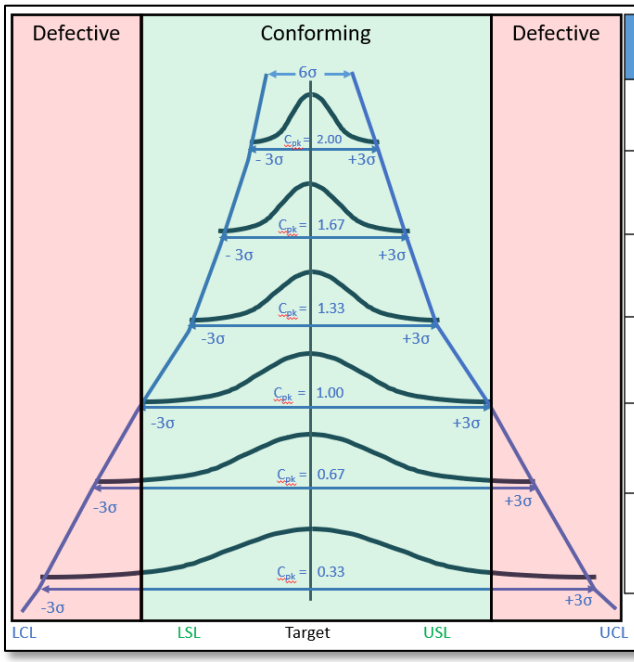


Figure 12: Less than capable process illustrated

5.5.5.1.3 Expected process yield based on calculated C_{pk} value

It should be clear, then, that processes possessing higher process capability will produce fewer defects; the higher the C_{pk}, the lower the defect rate. Figure 13 illustrates this point for a selection of C_{pk} values[19].



Sigma (σ) Level	Process Capability (C_{pk})	6σ as % of Tolerance	Process Yield	Defects (ppm*)	Evaluation
±6σ	2.00	50%	100.0000%	0.002	Extremely Capable
±5σ	1.67	60%	99.9999%	0.6	Very Capable
±4σ	1.33	75%	99.9937%	63	Capable
±3σ	1.00	100%	99.7300%	2,700	Marginally Capable
±2σ	0.67	150%	95.4500%	45,500	Incapable
±1σ	0.33	300%	68.2689%	317,311	Extremely Incapable

* ppm = parts per million

Figure 13: Defect rates vs. capability indices

[19] Assuming a centered process, defective parts per million for any sigma value can be calculated in Microsoft® Excel using the following formula: =2*(1-NORM.S.DIST(<Sigma Level>,TRUE))*1000000. For example, assuming a sigma level of ±3 (equivalent to C_{pk} =1), defective ppm =2*(1-NORM.S.DIST(3,TRUE))*1000000, yielding 2699.796 defective ppm.

5.5.5.1.4 The relationship between process capability and Lean/Six Sigma programs

The “six sigma” process improvement program pioneered by Motorola gets its name from their relentless pursuit of $C_{pk} > 2$. When C_{pk} reaches this level, the defect rate drops to 2 per billion. When the process variability reduction features of Motorola’s six sigma program are combined with the flow optimization and waste reduction features of the Toyota Production System, the result is a composite methodology known as “Lean Six Sigma”. Lean Six Sigma attempts to capture the best of what both concepts do well in a single consolidated package: pursue continuous efficiency improvements (lean) without sacrificing continuous effectiveness improvements (six sigma).

5.5.5.1.5 Ensuring process improvements yield positive returns on investment

Incapable processes require further process development, a product design change, or additional process verifications (for example, inspections) to ensure conforming product is delivered. All of these options incur cost, and the selected solution should demonstrate a positive return on investment. For this reason, caution is advised when considering whether to impose a minimum process capability requirement on contract. Not all process improvements yield a positive return on investment; it is possible for the cost of pursuing process improvements to exceed the resultant reduction in cost of quality. Nevertheless, C_{pk} values provide valuable insight into the opportunities, priorities, and potential cost benefits of variability reduction activities.

5.5.5.2 Lessons Learned

Lessons learned regarding implementation of the process capabilities best practice are presented in Table 36:

Table 36: Process Capabilities Lessons Learned

#	Lesson Learned
1	While there is no published universal requirement for processes to be at a certain capability level, AS9103, “*Variation Management of Key Characteristics*,” describes processes with a C_{pk} greater than 1.33 to be “capable”, and processes with a C_{pk} at or above 2.0 to be “highly capable”. Nevertheless, C_{pk} targets should be evaluated on a case-by-case basis, considering the cost and quality return on VR investment.

5.5.6 Production process verification

An effective MM Program verifies that processes, procedures, data, work instructions, tooling, and test equipment are capable of producing parts and assemblies that meet design requirements. The goal of PPV is to provide a high degree of statistical process control, ensuring that planned key/critical manufacturing process technologies (for example, machines, tooling), procedures (for example, data collection, work instructions), and product quality verification methods (for example, inspection gauges, test equipment) are capable of consistently producing products meeting design specifications within yield and capacity constraints.

5.5.6.1 Guidance

PPV's purpose is to *confirm* manufacturing processes are statistically capable of producing conforming parts. While the overarching purpose of PPV is similar to an MSV analysis, it differs in execution; MSV analysis relies on M&S (that is, virtual) data, PPV relies on actual production data. One common way to provide verification of the planned production process is to set up and produce parts on a "pilot line". Pilot lines replicate the planned production environment (for example, personnel skills and abilities, factory environmental conditions, shop floor machinery and work instructions, etc.), but on a smaller scale/at a lower rate. PPV can then be performed using actual process data gathered during production of pilot line units. When pilot line quantities are insufficient to deliver statistical significance, it may be necessary to lean on thorough reviews of work instructions, process control plans, estimates of capacities/yields to complete PPV. PPVs can also take advantage of process data available due to production of parts with similar features or through the use of coupons or samples. For example, a plating or powder coating line already in operation may provide data that can be used to verify its ability to produce coatings within a new product's specification limits. Verification is then accomplished through analysis of published manufacturing machine specifications supplemented by product data gathered during production of pilot line units. Because they are a detailed evaluation of the effectiveness of the production process and its ability to produce specification meeting, customer pleasing product, FAI/FAT results (see Section 0) may be used to support PPV.

5.5.6.2 Lessons Learned

Lessons learned regarding implementation of the production process verification best practice are presented in Table 37.

Table 37: Production Process Verification Lessons Learned

#	Lesson Learned
1	Since quality cannot be inspected or tested into complex, finished products, the goal of the quality system is to control each step of the manufacturing process to ensure the final product meets all specification requirements. PPV is a key tool in determining if this goal is likely to be met during production. It is through careful design and verification of the process and its controls that a manufacturer can establish a high degree of confidence that products manufactured from successive lots will be acceptable.
2	Validated models and simulations can be a PPV enabler when costly product mockups and/or a pilot line is impractical. This reinforces the importance and potential benefits of creating and maintaining validated "digital twin" product and process models that demonstrably, and accurately, represent operations on the production line.

5.5.7 First Article Inspections/First Article Tests

An effective MM Program performs First Article Inspections and First Article Tests, and ensures they are performed only on parts produced with production processes, documentation, and tooling. FAIs/FATs are conducted on new or modified parts that were produced using processes that have been validated (see Section 0), FAIs/FATs must be re-accomplished if the production line has been influenced (for example, introduction of new process, new machinery, new methods, new location), impeded (for example, natural or man-made events) or interrupted (that is, for more than two years). FAI's ensure that a new product sample, presented for inspection from the first production run, was produced according to engineering and design requirements. SAE AS6500 is not the first standard to recognize and highlight the benefits of FAI's. Contractors compliant with SAE AS9100 already have a requirement for FAI's imposed by paragraph 8.5.1.3, "*Production Process Verification*" which SAE AS9100 states "can be referred to as FAI". For some, SAE AS9102 may also be imposed; as its title, "*Aerospace First Article Inspection Requirement,*" suggests, this standard is dedicated explicitly to baseline

requirements for the performance and documentation of FAI's.

5.5.7.1 Guidance

First Article Inspections involve a detailed inspection of a *single product* built using verified production processes. FAIs also include reviews of in-process and acceptance testing procedures and results. FAIs should include auditing the process specifications, work instructions, inspection instructions, and test procedures to ensure they consistently reflect the engineering drawing requirements. FAIs should be re-accomplished when conditions warrant, such as:

- When a design change is introduced, affecting form, fit, or function of the part.
- When a change in manufacturing source(s), process(es), inspection method(s), location of manufacture, tooling, or materials that can potentially affect fit, form, or function is introduced.
- When a change in numerical control program or translation to another media is introduced that can potentially affect fit, form, or function.
- When natural or man-made events occur that may adversely affect the manufacturing process.
- When there has been a lapse in production for two years (or for a period otherwise specified by the customer).

If minor changes are anticipated to a mature design (that is, full FAI already completed), it may be possible to conduct a delta FAI focused on product design features that changed.

5.5.7.2 Lessons Learned

Lessons learned regarding implementation of the first article inspections/first article tests best practice are presented in Table 38.

Table 38: First Article Inspections/First Article Tests Lessons Learned

#	Lesson Learned
1	Detailed inspections of products need not be confined to first articles. If products from an established production program begin to experience quality problems post-delivery, Hardware Quality Audits (HQAs) may be used to identify/correct process issues that may have been introduced since FAI/FAT was initially accomplished. HQA's are "teardown" inspections conducted on randomly selected in-process or completed production units; they have a history of successfully detecting process quality problems. Like FAIs, HQAs can include an audit of the work instructions, inspection instructions, and test procedures to ensure they have maintained compliance with production drawings and specifications.

5.5.8 Supplier Management

An effective MM Program establishes and maintains a supplier performance tracking and management system. The system performs make/buy analysis, qualifies suppliers, identifies certain suppliers as key and/or critical, requires suppliers that maintain design authority to manage KCs/CCs, flows down requirements to lower tiers, assesses supplier health, and manages supplier risks (to include prevention of counterfeit parts).

5.5.8.1 Guidance

A subcontractor management plan should be developed which fully describes the supplier management effort. Supplier management activities should also be fully integrated into the overall program plans and schedules. The prime contractor's supplier management plan can also serve as a mechanism for incorporating GFP supplier activities and schedules into their overall program planning.

5.5.8.1.1 Key and Critical Supplier identification

A key supplier is one whose performance significantly impacts cost, schedule, technical, or supportability requirements, or is a critical supplier. A critical supplier is a supplier of critical parts. Key suppliers can exist at any level and may include suppliers of GFP. Several criteria are used to determine if a supplier is key:

- The supplier is "sole source" because of unique technologies or unique manufacturing capabilities.
- The supplier is a “single source” due to limited funds or production quantities.
- Excessive cost, schedule, or technical risk exists with no low-risk alternatives available.
- The requirements flow-down process (Figure 14) results in one or more of a supplier's product characteristics being deemed essential to attaining a system key performance parameter/requirement.

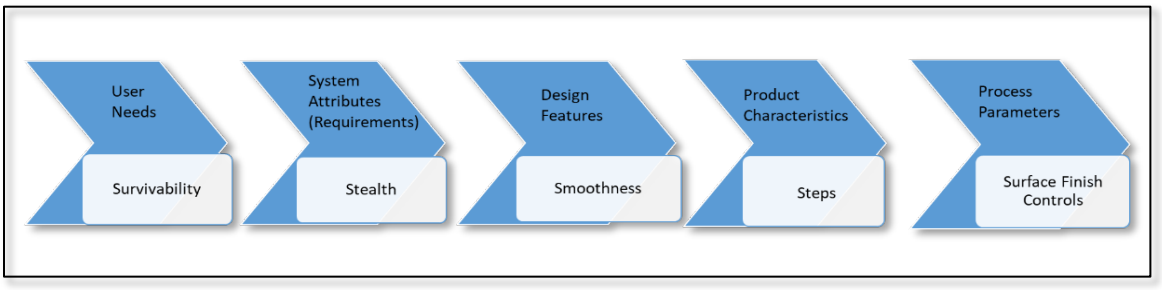


Figure 14: Requirements flow-down terminology

5.5.8.1.2 Managing key suppliers

The importance of supplier performance increases as the portion of weapon system requirements allocated to supplier products grows; it is not uncommon today for supplier activities to account for 70% or more of the total production cost. As supplier cost shares grow, so do responsibilities. Key suppliers may be responsible for the full range of system acquisition development activities, including performing design tasks, accomplishing design trade studies, maintaining risk management programs, and identifying key product/process characteristics. Key first-tier suppliers may further flow down design authority/responsibility to sub-tier suppliers. It is therefore essential to integrate key suppliers into program planning and development activities early so they can participate in requirement allocation and design trade study activities.

5.5.8.1.3 Managing critical suppliers

As weapon system complexity increases, individual elements of weapon systems become more complex, resulting in larger numbers of critical suppliers using larger numbers of critical processes to make parts, components, and subsystems. The supply chain is also becoming more diversified as DoD suppliers increasingly divide their attention between commercial and military pursuits. As the complexity, size, and scope of the supply chain increases, so does the supplier management challenge.

5.5.8.1.4 Privity of contract and flow-down requirements

Because of the common law doctrine of “privity of contract”, the Government has no legal relationship with subcontractors; supplier management is therefore a prime contractor responsibility. Nevertheless, the Government may impose flow-down requirements on the prime contractor and has a vested interest in the prime/subcontractor relationship. Meaningful supplier participation in the Integrated Product Team (IPT) process requires effective prime contractor communication of the program’s requirements and goals. For this reason, supplier management

is most effective when the government and prime contractor cooperate and speak with one voice. Prime contractors should have established criteria for key supplier selection that includes an assessment of the adequacy of their technical capabilities, augmented by evidence of successful performance on similar programs. As a best practice, prime contractors, should flow down SAE AS6500 requirements to their key suppliers and, in cooperation with their government customers, conduct initial and periodic audits to ensure compliance.

5.5.8.1.5 Associate Contractor Agreements and Government Furnished Property

If an Associate Contractor Agreement[20] (ACA) is implemented on a program, the agreement should include participation of key GFP suppliers. Such arrangements should allow insight into key GFP supplier activities sufficient for them to be fully integrated into the IMP. The prime contractor should notify the program office if they discover that a key GFP supplier's government contract possesses inadequate ACA requirements so that the requirements may be modified as needed for the program to be successfully executed.

5.5.8.2 Lessons Learned

Lessons learned regarding implementation of the supplier management best practice are presented in Table 39:

Table 39: Supplier Management Lessons Learned

#	Lesson Learned
1	Programs that fail to integrate key suppliers into overall schedules and plans struggle to meet program goals and requirements. When supplier capabilities are overlooked until after the design is finalized, flowed-down requirements are at risk. Symptoms include: Past performance data on supplier capabilities is insufficient/given far less weight than cost in selection activities Supplier performance lead times are overly optimistic containing little or no margin for delays Prime contractor insight into supplier schedule slips/other risk areas is limited
2	Proper contract language can be an effective tool to motivate prime contractors to implement supplier management best practices. Actions taken to proactively manage supplier risk throughout the supply chain (for example, successfully conducting critical supplier audits), are good candidates for award and/or incentive fees.

5.5.9 Supplier Quality

An effective MM Program establishes and maintains a supplier quality system. The system (1) assesses and monitors supplier performance with predictive quality indicators and on-site audits, (2) flows down quality requirements, including FAIs/FATs (with emphasis on verification and controlling KCs and CCs) to sub-tier suppliers, (3) delegates, as appropriate, MRB disposition authority to qualified suppliers, and (4) includes documented acceptance criteria.

5.5.9.1 Guidance

In DoD, assuring quality of subcontracted parts traditionally leaned on military specifications and standards. These specifications and standards became ubiquitous over time; suppliers came to understand them and rarely deviated from them. These military specifications and standards evolved over time for good reason; military missions and their operating environments often imposed tighter tolerances, more stringent processing standards, and longer life expectations

[20] ACAs are agreements between multiple contractors working on a single government project that specify requirements and safeguards for the sharing of information, data, technical knowledge, expertise, or resources.

than routinely seen in commercial applications. For example, if a commercial mobile phone component fails after 100 hours, the consequence is relatively small (for example, cost to the manufacturer who must replace the device, inconvenience to the customer who must wait for a replacement). If a similar component, produced in the same manner and on the same line as the phone component, fails on an F-35 avionics suite, the consequences might be catastrophic. Acknowledgment of this scenario is more than an academic exercise. Increasingly, DoD purchases parts for military use manufactured in facilities that share floor space and processes with similar commercial parts. While this is not, in and of itself, a bad thing, the DoD and aerospace industry should rigorously confirm critical components comply with military unique product and process quality standards that justifiably exceed standard commercial practices. Prime contractors, who frequently retain design authority for subcontracted parts, should therefore communicate product and process quality requirements to suppliers. When this important communication is not executed effectively, the government-contractor team will then, at a more costly and less convenient time, address the challenge of identifying, segregating, and dispositioning substandard parts, including some that may have already been installed on weapon systems.

5.5.9.1.1 Contract quality requirements flow down

RFP sections L and M should require bidding contractors to describe a robust approach to managing quality risks throughout the supply chain. The prime contractor's plans to identify and audit critical parts, processes, and key suppliers should be clearly expressed in the contract; it should also be reflected in the program's Quality Plan and/or the Systems Engineering Plan. Even when it is not a flow-down requirement, it is not uncommon for prime contractors to require third party quality certifications (for example, ISO 9001, AS9100, National Aerospace and Defense Contractors Accreditation Program (NADCAP)) of their suppliers; if so, the audit results may be available for review. Most quality system certifications require, after certification, periodic process compliance audits that verify continued compliance with the published quality system requirements.

5.5.9.1.2 Supplier Process Audits

While industry standard-based audits provide assurance that a supplier's quality system is consistent with formally published industry standards, they do not delve deeply into program-specific issues. Program offices may therefore choose to require product-focused Supplier Process Audits (SPA) to evaluate the finer details related to special processes producing program-critical parts. It is important that SPAs not focus only on the end-item because supplier process failures do not always manifest in visible, easily discovered ways in the final deliverable. Hidden defects can be introduced and if not detected quickly, endure throughout the system build process, often going unnoticed until exposed to an end-user due to a failure. Heat treatment of a titanium structural part provides a specific example of how this problem is easily avoided. The proper conversion of the titanium grain structure is the result of adding sufficient heat for an adequate amount of processing time. It takes a highly trained metals expert to verify the product characteristics once the process is completed; however, an auditor observing the process as it is being completed can readily see if the threshold temperatures are reached and held for the minimum required period of time. SPAs should therefore be performed periodically at suppliers responsible for critical processes, especially those used to produce parts that cannot be easily verified post-processing or easily accessed later in the build-up of the system.

5.5.9.2 Lessons Learned

Lessons learned regarding implementation of the supplier quality best practice are presented in Table 40:

Table 40: Supplier Quality Lessons Learned

#	Lesson Learned
1	Appropriate audit team membership and onsite activity are critical elements of successful supplier process audits. Supplier process audits are frequently performed when the supplier is responsible for producing a key or critical characteristic, often involving a process that itself is critical. To verify a critical process is being executed properly, the audit team should include experts with specialized process knowledge and experience (for example, a metallurgist for heat treatment processes). While many prime contractors have been performing supplier certification audits for some time, at times these audits have been accomplished as desktop audits by a buyer/contracting officer with perhaps a Quality Assurance specialist. Audits accomplished this way may involve simply verifying supplier flow-down requirements are captured on the Purchase Order (PO). Effective supplier process audits view this paperwork check as merely a starting point. The audit should culminate with the audit team personally observing a part being produced and inspected/tested. Although the initial accomplishment of this type of audit may appear similar to an FAI, supplier process audits differ in that they should be performed periodically to ensure the supplier's processes remain on track.
2	In one instance, tracing an issue to its source uncovered a dormant root cause; a lower tier supplier had deviated from the prescribed processes months earlier, resulting in the large quantity of defective parts present throughout the supply chain.
3	Some military systems consist of substantial components manufactured on commercial production lines. Many programs with a high percentage of commercial-derivative parts take a "hands-off" approach to the acquisition, assuming "commerciality" translates into quality even without conscientious management attention. This assumption has not always borne out to be true. When supplier process audits are not part of contractor's commercial quality management systems, the government customer should consider whether to require them contractually.

6 NOTES

6.1 Acronyms

Acronym	Abbreviation For
ACA	Associate Contractor Agreement
AFB	Air Force Base
ALC	Air Logistics Center
ASQ	American Society for Quality
BOM	Bill of Materials
BPR	Business Process Reengineering
CAD	Computer Aided Design
CC	Critical Characteristic
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CFR	Code of Federal Regulations
CLIN	Contract Line Item Number
CMP	Critical Manufacturing Process
CNC	Computer Numerical Controlled
CoC	Certificate of Conformance
CORRS	Cost of Rework, Repair, and Scrap
CoQ	Cost of Quality
COTS	Commercial Off-The-Shelf
Cp	Process Capability Index (assumes process is centered)
Cpk	Process Capability Index (allows possibility process may not be centered)
CPARS	Contractor Performance Assessment Reporting System
CPI	Continuous Process Improvement
CPP	Counterfeit Parts Prevention
CSI	Critical Safety Item
DA	Determinant Assembly
DCMA	Defense Contract Management Agency
DE	Digital Engineering
DFMEA	Design Failure Mode and Effects Analysis
DLA	Defense Logistics Agency
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DoD	Department of Defense
DSMC	Defense Systems Management College
DTC	Design to Cost
EMD	Engineering and Manufacturing Development
ERAI	Electronic Resellers Association International
ERP	Enterprise Resource Planning
FAA	Federal Aviation Administration
FAI	First Article Inspection
FAT	First Article Test
FMECA	Failure Mode, Effects, and Criticality Analysis
FOD	Foreign Object Debris
FRP	Full-Rate Production
GAO	Government Accountability Office
Gage R&R	Gage Repeatability and Reproducibility
GFP	Government Furnished Property
GIDEP	Government-Industry Data Exchange Program
GT	Group Technology
HQA	Hardware Quality Audit
IMP	Integrated Master Plan

Acronym	Abbreviation For
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
IRT	Independent Review Team
ISO	International Organization for Standards
JDMTP	Joint Defense Manufacturing Technology Panel
JDRS	Joint Deficiency Reporting System
KC	Key Characteristic
KMP	Key Manufacturing Process
LCD	Liquid Crystal Display
LCL	Lower Control Limit
LOB	Line of Balance
LRIP	Low-Rate Initial Production
LSL	Lower Specification Limit
M&Q	Manufacturing and Quality
M&S	Modeling and Simulation
MDA	Missile Defense Agency
MII	Manufacturing Innovation Institute
MIT	Massachusetts Institute of Technology
MM	Manufacturing Management
MOA	Memorandum of Agreement
MRA	Manufacturing Readiness Assessment
MRB	Material Review Board
MRL	Manufacturing Readiness Level
MRO	Maintenance, Repair, and Overhaul
MRP	Material Requirements Planning
MRP II	Manufacturing Resource Planning
MSA	Material Solution Analysis (Acquisition Phase context) Measurement System Analysis (MM Program Requirement context)
MSV	Manufacturing System Verification
NADCAP	National Aerospace and Defense Contractors Accreditation Program
O&A	Over and Above
OCM	Original Component Manufacturer
OEM	Original Equipment Manufacturer
OSD	Office of the Secretary of Defense
OUSD R&E	Office of the Under Secretary of Defense for Research and Engineering
PC	Production Certificate
PCM	Production Cost Model
PDCA	Plan-Do-Check-Act
PDR	Preliminary Design Review
PFMEA	Process Failure Mode and Effects Analysis
PFMECA	Process Failure Mode, Effects, and Criticality Analysis
PMS	Production Management System
PO	Purchase Order
PPP	Program Protection Plan
PPV	Production Process Verification
PRR	Production Readiness Review
QMS	Quality Management System
RF	Realization Factor
RFP	Request for Proposal
ROM	Rough Order of Magnitude
RPN	Risk Priority Number
SAE	Society of Automotive Engineers

Acronym	Abbreviation For
SE	Systems Engineering (Section 3.1) Support Equipment (Elsewhere)
SEP	Systems Engineering Plan
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
SME	Subject Matter Expert
SOW	Statement of Work
SPA	Supplier Process Audit
SPC	Statistical Process Control
SRP	Standard Repair Procedure
SRR	Scrap, Rework, and Repair
ST	Special Tooling
STE	Special Test Equipment
TDP	Technical Data Package
TLCSM	Total Life-Cycle Systems Management
TMRR	Technology Maturation and Risk Reduction
TOC	Total Ownership Cost
TPM	Total Preventive Maintenance
TRL	Technology Readiness Level
UCL	Upper Control Limit
UID	Unique Identification Data
USL	Upper Specification Limit
VIN	Vehicle Identification Numbers
VR	Variability Reduction
VSA	Variation Simulation Analysis
VSM	Value Stream Map
WIP	Work In Process (Work in Progress)

6.2 Subject Term (Keyword Listing)

CRITICAL CHARACTERISTICS
CRITICAL MANUFACTURING PROCESSES
FACTORY EFFICIENCY
KEY CHARACTERISTIC
KEY SUPPLIERS
MANUFACTURING MANAGEMENT SYSTEM
MANUFACTURING READINESS LEVELS
PROCESS CONTROL
PROCESS FAILURE MODES EFFECTS ANALYSIS
PROCESS VALIDATION
PRODUCIBILITY
PRODUCTION PROCESS VERIFICATION
PRODUCTION READINESS REVIEWS
QUALITY
QUALITY MANAGEMENT SYSTEM
STATISTICAL PROCESS CONTROL
SUPPLIER MANAGEMENT
SUPPLIER PROCESS AUDITS
VARIABILITY REDUCTION
VIRTUAL MANUFACTURING

7 CHANGES FROM PREVIOUS ISSUE

Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of the changes.

Appendix A
Benefits of an Effective MM Program

A.1 SCOPE

This appendix expands on the broader benefits of an effective MM Program. It does so by focusing on the two primary benefits, which are effectiveness and efficiency. This appendix describes how the best practices/tools of a MM Program contribute to these benefits. It is only when many of these tools are used in concert and at the appropriate time that the full benefit of their use may be achieved. As it pertains to the MM Program collection of requirements, the "whole" is indeed greater than the sum of the individual parts.

A.2 THE BALANCING ACT: MANUFACTURE THE RIGHT THING, MANUFACTURE THE THING RIGHT

Fundamentally, an MM Program should accomplish two things: (1) ensure a product is *effectively* designed so it can be repeatably produced (that is, manufacture the right thing), and (2) ensure the production system *efficiently* produces the product design repeatably (that is, manufacturing the thing right). The former requires careful planning, the latter vigorous execution. An effective MM Program ensures both the *planning,* and the *execution* phases of weapon system development and delivery are being accomplished *effectively* and *efficiently*.

A.2.1 Manufacturing effectiveness

Figure 15 illustrates that effectiveness is a measure of how well a product satisfies the customer, which is the primary focus of a QMS. An advanced QMS addresses measures of both process *capability planning rigor* and process *capability execution effectiveness*. Process capability effectiveness is directly impacted by M&Q SME participation in original product designs and subsequent continuous product improvement efforts. The goal of the M&Q SME participation is to ensure process **capabilities are sufficiently mature to effectively produce** products that satisfy customer requirements.

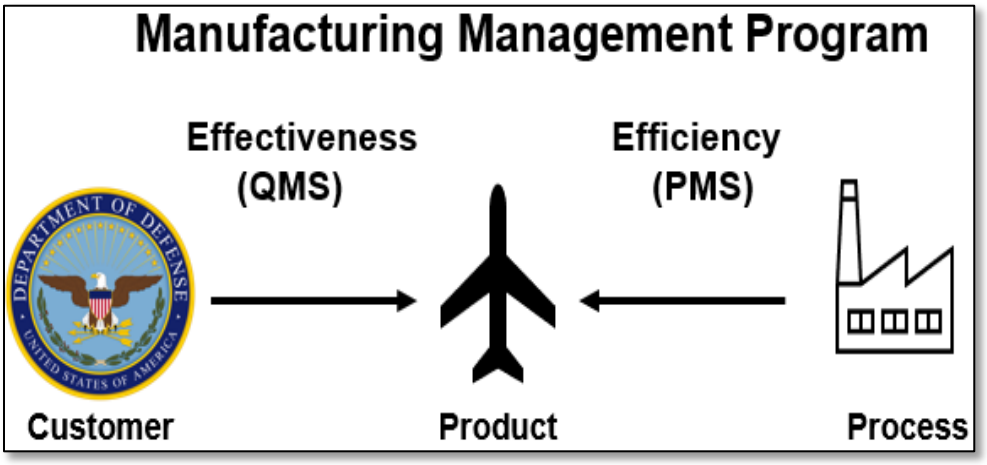


Figure 15: MM and the Customer-Product-Process relationship

A.2.2 Manufacturing efficiency

Efficiency is a measure of how well the process produces the product, which is the focus of a PMS. An advanced PMS addresses measures of both process *capacity planning rigor* and process *capacity execution efficiency*. Measures of efficiency are directly impacted by M&Q SME participation in the development of initial manufacturing process designs and subsequent

continuous process improvement efforts. The goal of M&Q SME participation is to ensure process **capacity is sufficiently available to efficiently produce** product quantities that satisfy customer demand.

A.2.3 How an effective MM Program supports manufacturing effectiveness and efficiency

The collection of requirements described in this handbook, which mirrors those presented in SAE AS6500, represent tools and techniques considered best practices by both government and industry. When included as elements of an overall MM Program, these tools and techniques will make the process of manufacturing process capability and capacity planning and execution more effective and efficient (Table 41).

Table 41: How MM supports effective & efficient manufacturing planning & execution[21]

Phase	Goal	Best Practice	Surveillance and Control
Planning Manufacture the right thing	MMP Goal 1 Design Producibility Influence product design decisions to ensure available process capabilities are sufficiently mature to meet product specifications MMP Goal 2 Production Readiness Influence production process decisions to ensure process capacity is sufficiently available to meet customer demand at lowest possible cost	QMS Goal 1 Plan for Process Effectiveness 5.2.1: Producibility Analysis 5.2.2: Key and Critical Characteristics 5.2.3: Process Failure Modes Effects Analysis 5.3.1: Manufacturing Feasibility Assessments PMS Goal 1 Plan for Process Efficiency 5.4.2: Materials Management 5.4.3: Manufacturing Technology Development 5.4.4: Cost 5.4.5: Manufacturing Modeling and Simulation 5.4.6: Manufacturing System Verification 5.4.7: Manufacturing Workforce 0: Tooling/Test Equipment/Facilities 0: Measurement System Analysis	Survey and Improve Production Planning 5.3.2: Manufacturing Readiness Assessments 0: Production Readiness Reviews 0: Manufacturing Plan
Execution	MMP Goal 3	QMS Goal 2	Survey and Improve

[21] This table is presented to organize thoughts, not compartmentalize them. Assuredly, many of the tools addressed in SAE AS6500 cross the goal “boundaries” shown. A concession is made, for example, that the “Cost” requirement not only supports planning activities but also execution tasks; however, the first and arguably greatest impact is made when costs are modeled, and that model is used during development to aid cost-driving decision-making. The lack of pure orthogonal fidelity does not, however, diminish the overall purpose here, which is to provide a useful abstract organizational structure that logically categorizes the individual tools according to how they chiefly support the overarching goals of an effective MMP.

Appendix A
Benefits of an Effective MM Program

Table 41: How MM supports effective & efficient manufacturing planning & execution[21]

Phase	Goal	Best Practice	Surveillance and Control
Manufacture the thing right	Defect Prevention Measure and manage process capability to ensure it is producing customer-satisfying product at highest desirable level of quality	Execute Processes Effectively 5.5.4: Variability Reduction 5.5.5: Process Capabilities 5.5.6: Production Process Verification 5.5.7: First Article Inspections/First Article Tests 5.5.8: Supplier Management	Production Execution 5.5.2: Manufacturing Surveillance 5.5.3: Continuous Improvement
	MMP Goal 4 Lean Operations Measure and manage process capacity to take optimal advantage of available, capable manufacturing processes	PMS Goal 2 Execute Processes Efficiently 0: Production Scheduling and Control 5.5.3: Continuous Improvement	

During the Planning phase, the QMS pursues effectiveness via a producible product design while the PMS plans for efficiency through production process maturity. During the Execution phase, the QMS pursues activities that prevent product defects while the PMS strives for increasingly efficient operations. Both the planning and execution phases employ activities to monitor and control risk; the identified surveillance and improvement oversight activities support the M&Q SME's participation in the overall program risk management program.

A.2.4 Balancing efficiency and effectiveness

Both the QMS and the PMS should balance each other. The alternative course, at the extremes, illustrates the point: A PMS completely unhindered by an effective QMS produces product nobody wants; a QMS unchallenged by an efficient PMS produces product nobody can afford. Since neither extreme accomplishes anything productive, a balance should be struck. In the end, conscientiously developed products accompanied by diligent continuous process effectiveness and efficiency improvement activities increases the likelihood that well-designed products are well produced. The following sections elaborate on each of the surveillance and best practice categories of requirements presented in Table 14.

A.3 PLANNING PHASE: MANUFACTURE THE RIGHT THING

During product development, the manufacturing management emphasis is on planning for success. This entails ensuring (1) a QMS that ensures a producible product design that meets customer requirements and (2) a PMS that ensures production resources with demonstrated capabilities to produce that design are ready.

A.4 PLANNING FOR PROCESS EFFECTIVENESS: DESIGN PRODUCIBILITY

The requirements in this category include all the ***planning*** (that is, design participatory) steps taken by M&Q SMEs during product development to ensure product designers anticipate available manufacturing ***capabilities effectively*** (that is, correctly). The transition from development to production is challenging and has been for a very long time. DoD 4245.7-M,

"Transition from Development to Production" describes the challenge, and its source, this way:

> *"Many programs simply cannot succeed in production, despite the fact that they've passed the required milestone reviews. These programs can't succeed for technical reasons, notwithstanding what is perceived as prior management success related to DoD acquisition policy. A poorly designed product cannot be tested efficiently, produced, or deployed. In the test program there will be far more failures than should be expected. Manufacturing problems will overwhelm production schedules and costs. The best evidence of this is the "hidden factory syndrome" with its needlessly high redesign and rework costs. In addition, field failures will destroy operational and training schedules and increase costs. The transition process is very broad, and it is impacted by activities that are, or more accurately, are not done in the early design and test activities.[22]"*

A.5 PLANNING FOR PROCESS EFFICIENCY: PRODUCTION READINESS

The requirements in this category include all the *planning* steps taken by M&Q SMEs to ensure adequate process *capacity* is in place to produce desired product quantities *efficiently*, that is, at the lowest possible cost. Ineffective or late manufacturing planning is highlighted in DoD 4245.7-M as historically a major source of manufacturing risk:

> *"Involvement of production and manufacturing engineering only after the design process has been completed is a fundamental error and a major transition risk. Consequences of late involvement are: (1) an extended development effort required for redesign and retest of the end item for compatibility with the processes and procedures necessary to produce the item, and (2) lower and inefficient rates of production due to excessive changes in the product configuration introduced on the factory floor. Increased acquisition costs and schedule delays are the result of this approach.[23]" (Emphasis added)*

The requirements in this section, taken together, represent the collection of activities that support preparations for optimum use of available production capacity. All of these planning activities are essential elements of manufacturing/production readiness to execute.

A.5.1 Planning phase surveillance and control: survey and improve production planning

These activities represent the planning phase's "check and act" portion of Shewhart's "plan-do-check-act" cycle. They also align with the program manager's "risk monitoring" and "risk control" activities respectively. The first two requirements, Manufacturing Readiness Assessments (MRA) and Production Readiness Reviews (PRR) represent the check/monitor activities, together they involve periodic, milestone-based assessments of the design producibility (Section 0) and production readiness (Section 0) activities. PRRs receive special attention due to their focus on a particularly critical milestone given special attention in DoD 4245.7-M: the transition from development to production. Much of the assessment accomplished during a PRR is also based on MRL criteria, specifically MRL 8 for Low-Rate Initial Production (LRIP) and MRL 9 for Full-Rate Production (FRP). Manufacturing Maturation Plans are required when any of these MRL threads and their associated MM Program requirements fail to meet standard expectations, for example, failure to meet MRL 8 before LRIP begins (see Figure 3). The plans

[22] DoD 4245.7-M, (1985). The Transition from Development to Production, Assistant Secretary of Defense, Acquisition and Logistics. p. 1-1.
[23] DoD 4245.7-M, (1985). The Transition from Development to Production, Assistant Secretary of Defense, Acquisition and Logistics. p. 5-2.

for addressing the design producibility and production readiness requirements should be captured and maintained in the third requirement, the Manufacturing Plan. Though not explicitly called out as a separate requirement at this level, action, in the form of Manufacturing Maturation Plans, are required when any of these oversight activities identify failures to meet standard expectations, for example, failure to meet MRL 8 before LRIP begins (see Figure 3). The three activities together represent the survey/monitor risk functions of production planning. Manufacturing Maturation Plans are the tool used for production planning improvement/risk control.

A.6 EXECUTION PHASE: MANUFACTURE THE THING RIGHT

During production, the manufacturing management emphasis is on executing successfully. This entails providing (1) a QMS focused on defect prevention and continuous improvement and (2) a PMS that demonstrates sufficient capacity and capability to produce efficiently.

A.6.1 Executing effectively: defect prevention

An effective QMS, focused on defect prevention, is essential to delivery of operationally safe, suitable, and effective weapon systems that meet contractual requirements. The requirements in this category include all the *execution* steps taken by M&Q SMEs during the production process to ensure *capable* processes produce customer-satisfying product *effectively*, that is, at highest desirable level of quality.

A.6.1.1 The limitations of inspection

Though it may be the best option at times, relying on inspections to control quality is an imperfect solution. Visual inspections are limited in their capability and can be error-prone, meaning even if every item is inspected there remains a distinct possibility that nonconforming product will escape to a downstream customer. Even 100% inspection has been shown to be less than 100% effective in preventing quality escapes. The use of go/no-go gauges as a poka-yoke alternative to visual inspection is an industry best practice that simplifies and improves effectiveness of human inspections, when necessary. Even when executed in the best possible way, a problem remains with inspection-based quality systems; they do not improve product quality, they merely strive to prevent delivery of defective product to downstream customers and ultimately to end users. Because of this major shortcoming, quality systems that rely exclusively on inspection (that is, defect detection/correction) are ceding ground to quality systems based on defect prevention. A carefully executed QMS ensures then, through monitoring, measurement, defect prevention, and continuous improvement efforts, as-delivered configurations match as-designed/tested configurations. It is important to note that QMS responsibilities extend beyond the quality assurance organization; advance quality systems hold each functional area responsible for the quality of their work and empower them to make key decisions to ensure and improve the quality of that work.

Appendix A
Benefits of an Effective MM Program

A.6.1.2 Elements of an effective QMS

Program Office contract Statement of Work (SOW) language, appropriately tailored, should require contractors to ensure QMS requirements[24] are clearly documented, effectively deployed, regularly monitored, and routinely maintained. Fortunately, these requirements need not be developed from scratch. The International Organization for Standards (ISO) has published a series of quality management standards describing elements of an effective QMS; among them ISO 9001, “Quality Management System – Requirements”. Various groups have supplemented ISO 9001with industry-unique requirements. For example, The International Aerospace Quality Group has also published a QMS standard specifically for the aerospace and defense industry, SAE AS9100, “Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations”. Based on and traceable to ISO 9001, this standard elaborates on unique aerospace and defense industry requirements (for example, key characteristics, prevention of Foreign Object Debris (FOD)). Program offices routinely cite these standards in DoD contracts when specifying QMS requirements. According to these and other published quality program standards, effective quality management systems possess the following attributes:

- They require express leadership commitment to quality and a customer focus.
- They assure control of product life-cycle processes: design, development, subcontracting, production, and sustainment.
- They ensure processes are designed to meet customer requirements using only steps that add value to the product. Processes are assessed at all levels and in all functions, within organizations and at the interfaces between organizations.
- They employ a closed-loop Plan-Do-Check-Act (PDCA) cycle to ensure process deployment plans are defined, implemented, measured, and improved. They accomplish verification and validation of suppliers, personnel, processes, tests, and products.
- They maintain control of software deployed in manufacturing resources (for example, software used to perform Computer Aided Design (CAD), Computer Numerical Controlled (CNC) machining, measurement, and test) to prevent unauthorized changes.
- They emphasize defect prevention methods and best practices (for example, Key Characteristic (KC) management, determinate assembly) over defect detection/correction. When defects do occur, they maintain control of nonconforming products, perform root cause analyses, and execute appropriate corrective actions.
- They accomplish Measurement System Analysis for tools/methods used to inspect, validate, or verify products and processes.
- They produce product validation and surveillance plans, including physical configuration audits and first article inspections.

A.6.1.3 The importance of QMS vigilance

Even a properly specified and carefully designed QMS can fail in execution. The following actual

[24] Commercial derivative programs, for example, DoD aircraft built under the authority of a Federal Aviation Administration (FAA) Production Certificate (PC), will rely on other agency quality requirements and processes. Federal Aviation Regulation Part 21 states that a “holder of a production certificate must establish and describe in writing a quality system that ensures that each product and article conforms to its approved design and is in a condition for safe operation.” M&Q SMEs should determine the extent to which FAA QMS oversight meets the needs of the DoD, where gaps may exist, and how to address those gaps. Often the FAA, like the DoD, relies heavily on SAE AS9100 and ISO 9001 to drive QMS requirements.

experiences demonstrate the importance of vigilance:

- When quality issues are inevitably found, root cause analyses are not always performed rigorously. Material Review Boards (MRBs), charged with discerning the cause of a nonconformance, are often drawn to what seems the most obvious, though not necessarily correct, solution. Process Failure Modes and Effects Analysis (Section 0), Continuous Improvement (Section 0) and Variability Reduction (Section 0) tools should be used to conduct a thorough analysis of gathered surveillance data (Section 0) to properly determine the true root cause.
- Prototype and technology demonstration programs may employ shortcuts in their quality management systems. Attention to detail and process control are no less important when dealing with complex, never-before-used technology. Intricate test efforts can fail due to improper use or assembly of the least expensive part.
- There is a natural tendency to focus on identified quality issues in isolation. Failure to occasionally take a step back and consider the big picture can have consequences. It is possible for numerous minor non-conformances to accumulate and become a major nonconformance. MRBs should therefore gather data providing insight into the possible relationships and cumulative effects of previously identified non-conformances. Unique Identification Data (UID) is an analysis enabler; UIDs can be used in a manner similar to how Vehicle Identification Numbers (VIN) are used to uniquely identify automobiles and track their maintenance histories.

In essence, an effective QMS determinedly and vigorously addresses the Design Producibility, Defect Prevention, and associated oversight best practices of an MM Program (refer again to Figure 8). When QMS systems are effectively implemented, conforming, customer pleasing product is delivered to the warfighter.

A.6.2 Executing efficiently: lean operations

The requirements in this category include all the *execution* steps taken by M&Q SMEs during the production process to ensure adequate process *capacity* produces desired product quantities *efficiently*, that is, at the lowest possible cost.

A.6.2.1 The evolution of the modern factory

James P. Womack Daniel T. Jones, and Daniel Roos “introduced” the concept of Lean Production (coined a phrase, actually) to the American public in *The Machine that Changed the World*[25], which was first published in 1990. *Lean Thinking*[26], the follow-on “how-to” volume, was published in 1995. Taiichi Ohno had been perfecting his Toyota Production System, onto which the term Lean Production was thrust, since shortly after World War II until his death in 1990. Mr. Ohno credited his inspiration in part to Henry Ford, the discoverer of lean production’s “special case” – mass production (circa 1913). Henry Ford benefited from the work of Frederick Taylor and Frank & Lillian Gilbreth. These founders of the Industrial Engineering profession pioneered scientific management principles and influenced industrial analysis and efficiency just prior to and after the turn of the 20th century. They believed it was possible to pursue ideal production (via methods engineering) and highlight failure to achieve it (via work measurement data collection and analysis). The intent and objective of the work of Taylor and the Gilbreths was to continuously pursue and maintain efficient production processes, which is to say processes that were devoid of waste. They defined waste as inefficiency, which is any variance from value-

[25] Womack, J, Jones, D, and Roos, D, (1990). The Machine that Changed the World. Productivity Press.
[26] Womack, J. and Jones, D. (1996). Lean Thinking. Simon & Schuster.

added standard work. Pictorially, the outgrowth of the Taylor and Gilbreth concepts can be represented as shown in Figure 16.

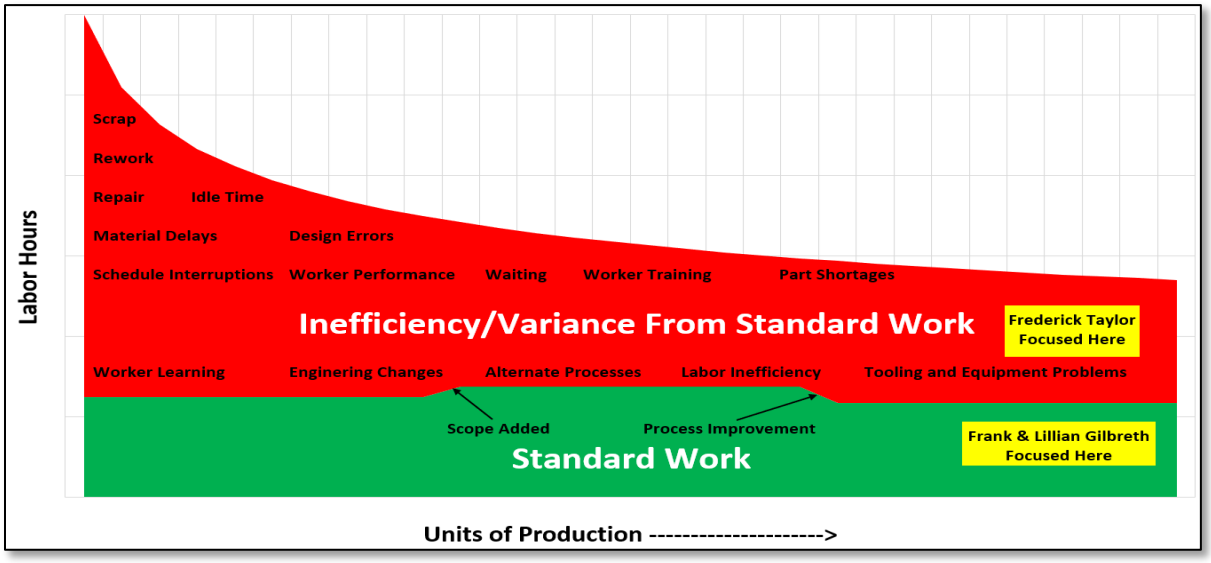


Figure 16: Waste defined as variance from the standard

A.6.2.2 Early focus on improving worker productivity

Methods Engineering was largely the focus of Frank and Lillian Gilbreth. What drove them was finding the “one best method” via analysis of every motion accomplished in the performance of a task. Improvement in this area would be represented by reductions in the standard. Their work eventually led to the development of pre-determined time systems. Finding and eliminating inefficiency was largely the domain of Frederick Taylor (which of course did not make him very popular in his day). Mr. Ohno would later call variance from ideal/standard “muda”, which when translated most literally into English means “waste”. Over the years many tools that attack these directly measurable elements of waste have been developed. Table 42: Elements of a PFMEA is a sampling of some of them.

Table 42: Waste reduction tools

Waste	Tool/Technique	Effect
Worker Learning	Standard Work Instructions	Reduces the time it takes for workers to “come up to speed” (that is, down the learning curve).
Design Errors	Computer Aided Design (CAD)	Allows designs to be evaluated “virtually”. Design errors are caught before they ever reach the production floor when changes are more costly to implement.
Engineering Changes	Integrated Product and Process Development (IPPD)	Helps ensure a producible product that need not be changed because of a design that assumed process capabilities not available.
Tooling and Equipment Problems	Total Preventive Maintenance (TPM)	Equipment and tools that are kept in ideal operating condition produce specification-meeting quality product.

Still, some elements of inefficiency seemed to elude best efforts to reduce them. Notice the process execution variance elements remaining, for example, material delays, waiting, part

shortages, alternate processes, and schedule interruptions. What do they all have in common? They all involve interruptions in or deviations from the normal flow of production. Certainly, a way of attacking these elements could be devised.

A.6.2.3 Shifting focus to improving factory flow productivity

Henry Ford believed that mass-produced cars could sell at a price within reach of the average American family. And he was right. His Model T sold 15 million between 1908 and 1926. By adopting mass-assembly methods and introducing the moving assembly line, Henry Ford revolutionized automobile production. The moving assembly line concept attacked the heart of the flow-related elements of inefficiency. What he stumbled upon was what eventually became known as lean production's "special case": mass production in an environment of high production quantity (that struggles to keep up with demand) and minimal or no variety. These two simplifying ... and perfectly acceptable in that day ... conditions essentially and effectively jettisoned most of the complexity we see in today's production environments. What happened to change Henry Ford's simplifying assumptions? Some have suggested that generations of depression-deprived consumers began moving on. After the conclusion of World War II, which encouraged measures of self-deprivation as a way of supporting the war effort, the economy began to take off. New generations of Americans were born into a world with more disposable income. Complexity in the forms of variety and competition (driving more specialized demand below full-rate capacity) began to introduce itself. Producing a single product at capacity no longer satisfied customer requirements. Production management techniques needed to evolve. For a long time, they did not. The production problem that Henry Ford did not deal with effectively was a market environment that demanded product variety. And quite frankly, in his day and time, he did not have to. When you are the only game in town, it is possible to get away with saying, as Henry Ford is quoted in his autobiography, *My Life and Work*, "Any customer can have a car painted any colour that he wants so long as it is black"[27]. Henry Ford had perfected the "special case" of lean. Womack and Jones summarize it this way in their book, *Lean Thinking*:

> *"Henry Ford and his associates were the first people to fully realize the potential of flow. Ford reduced the amount of effort required to assemble a Model T Ford by 90 percent during the fall of 1913 by switching to continuous flow in final assembly. Subsequently, he lined up all the machines needed to produce the parts for the Model T in the correct sequence and tried to achieve flow all the way from raw materials to shipment of the finished car, achieving a similar productivity leap. But he only discovered the special case. His method only worked when production volumes were high enough to justify high-speed assembly lines, when every product used exactly the same parts, and when the same model was produced for many years (nineteen in the case of the Model T). In the early 1920's, when Ford towered above the rest of the industrial world, his company was assembling more than two million Model Ts at dozens of assembly plants around the world, every one of them exactly alike.[28]"*

A.6.2.4 The generalization of mass production

Mr. Taichi Ohno did not believe in his day that he possessed the luxury of maintaining Ford's approach. He therefore needed to try something different, to tweak the system. Over the course of many years of trial and error, Mr. Ohno developed a production system that eventually became known as the Toyota Production System. Americans, thanks to Womack and Jones,

[27] Ford, Henry. (1922). My Life and Work. Doubleday, Page & Company. New York. p. 72.
[28] Womack, J. and Jones, D. (1996). Lean Thinking. Simon & Schuster. pp. 22-23.

call it “lean production”, who describe its evolution this way:

> *“After World War II, Taiichi Ohno and his technical collaborators, including Shigeo Shingo, concluded that the real challenge was to create continuous flow in small-lot production when dozens or hundreds of copies of a product were needed, not millions. This is the general case because these humble streams, not the few mighty rivers, account for the great bulk of human needs.[29]”*

The exploration of the humble streams led Mr. Ohno to discover less obvious sources of waste scattered everywhere, even within that which was considered standard work. Indeed, one of the things that singles out lean production is the focus, at least initially, on the what has been called the “hidden factory” inefficiency--parts and subassemblies waiting to be processed--as a primary target for reduction/elimination. This is the aspect of lean production that Henry Ford’s good idea pioneered. The term “hidden factory” was coined since most production monitoring systems historically focused on capturing data about parts being processed, not on those awaiting processing. The waiting parts sit quietly and largely ignored (by management, anyway since management personnel are not the ones stumbling over piles of work-in-process inventory in the course of accomplishing their daily work) until one day the factory can no longer contain them.

A.6.2.5 Identifying and attacking hidden factory waste

Gilbreth obsessed over finding and executing the best manufacturing method; focus was on reducing inefficiency associated with machine/operator interactions with parts being produced (see Appendix D for a discussion of labor standards and operational efficiency). Taiichi Ohno, the father of the Toyota Production System, expanded the scope of waste (or “muda” in Japanese) elimination by including “hidden factory” waste, or waste that occurs in a factory between processes rather than within them. Four of Ohno’s seven elements of “muda” (in bold below) can be tied directly to this specific hidden factory form of inefficiency either as a cause or a symptom. Ohno’s seven are:

1. defects (in products)
2. **overproduction of goods not needed**
3. **inventories of goods awaiting further processing or consumption**
4. **unnecessary processing**
5. unnecessary movement (of people)
6. unnecessary transport (of goods)
7. **waiting (by employees for an upstream activity to finish)**

Not only does Ohno concentrate on the hidden factory elements of inefficiency, the first four of Womack & Jones’ five steps to lean conversion drive predominantly toward the objective of eliminating this same inefficiency. Their five steps are shown in Figure 17.

[29] Womack, J. and Jones, D. (1996). Lean Thinking. Simon & Schuster. p. 23.

Appendix A
Benefits of an Effective MM Program

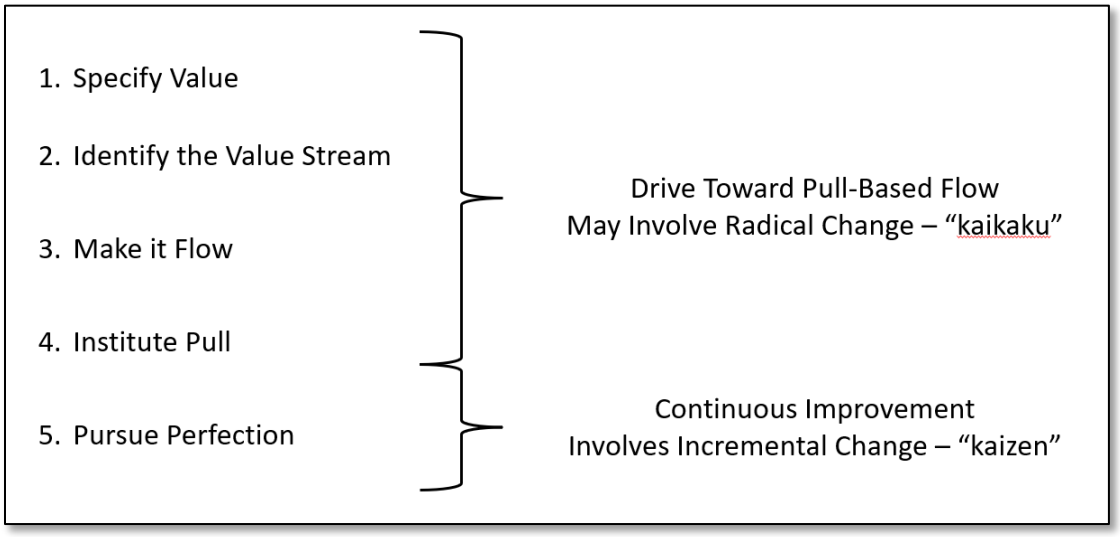


Figure 17: Five steps to lean implementation

A lean production expert walking the floor of a manufacturing facility for the first time will focus heavily on identifying batches of parts awaiting the next operation and large quantities of work in process. These are indicators that the process needs to be completely rethought in order to become lean. The remaining elements of waste, and the tools (e.g., Statistical Process Control (SPC), TPM, etc.) employed to reduce them fall into the pursuit of perfection category. They assume the production process flow is optimized and all that needs to be done is to keep it functioning properly.

A.6.2.6 Implementing lean operations requires system-level thinking

Many companies have fallen into two common lean implementation traps. The first is to attempt to implement lean production piecemeal, without a system view. The second is to pursue it on a small scale, without an emphasis on continuous improvement over time. It should be clear, based on the discussion of lean production just presented, that neither approach will harvest the benefits of *system-wide, continuous process improvement* programs. Upon evaluating lean concepts and comparing them to published experiential anecdotes, it became clear that lean was nothing new when considering only its individual parts. Lean concepts did differ, however, perhaps more meaningfully than any other catchphrase that has come along in a while, in how they employed and took advantage of a systemwide view of production. Lean thinking required this since its focus on what happens to parts inter-process (where they sit idly while waiting for the next process) required an "extra-process" (system-wide) point of view.

A.6.3 Execution phase surveillance and control: survey and improve production execution

These activities, surveillance and improvement, represent the execution phase's "check and act" portion of Shewhart's "plan-do-check-act" cycle. They also align with the program manager's "risk monitoring" and "risk control" activities respectively. Manufacturing surveillance represents the "check/monitor" activity; it involves regular monitoring of production performance, preferably through rigorous data collection. Improvement represents the "act/control" activity; it involves taking positive action to improve the efficiency and effectiveness of production processes based on opportunities revealed as a result statistical analysis of collected, reliable process data.

Appendix B
Key and Critical Characteristics

B.1 Scope

This appendix expands on the importance of defining and controlling Key Characteristics (KCs) and Critical Characteristics (CCs). It defines KCs and CCs and their relationships to the manufacturing process. It also explains the importance of controlling and/or eliminating KCs, when possible.

B.1.1 Key characteristic defined

According to SAE AS6500, a Key Characteristic (KC) is "… an attribute or feature whose variation has a significant influence on product fit, form, function, performance, service life, or producibility that requires specific actions for the purpose of controlling variation." It is important to recognize that "whose variation" modifies "an attribute or feature" of the product. The implication is that a KC is a product attribute/feature that performs best at nominal; deviation from that nominal has a costly effect on performance, consistent with Genichi Taguchi's loss function assertion. Taguchi's loss function recognizes that quality does not suddenly plummet at the tolerance level (conventional quality loss understanding known as "goal posting"), it drops gradually as variation from the nominal value increases. The contrast between the two views is presented in Figure 18.

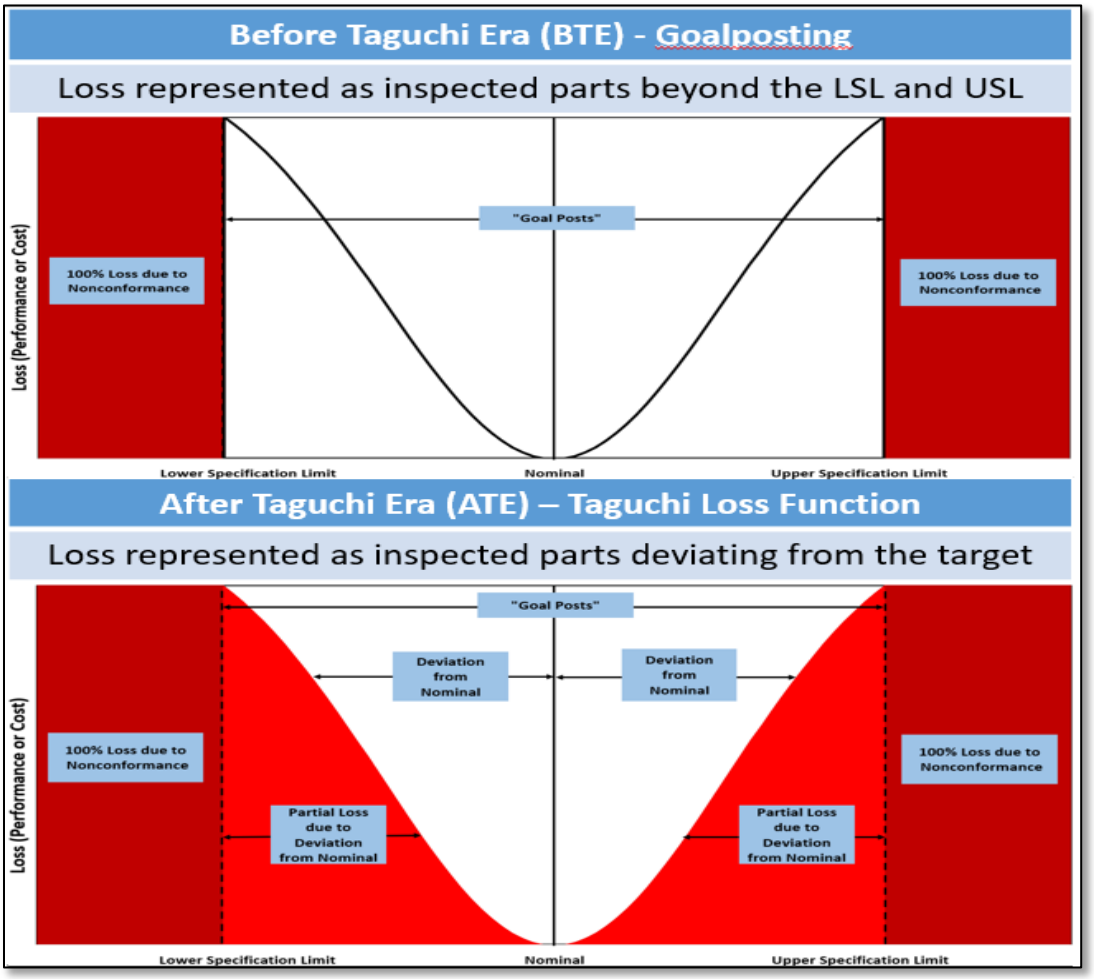


Figure 18: Conventional vs Taguchi understanding of quality loss

Appendix B
Key and Critical Characteristics

B.1.2 Critical characteristic defined

According to SAE AS6500, a Critical Characteristic (CC) is “a characteristic whose variation has a significant impact on human safety or could cause a catastrophic failure resulting in loss of life, permanent disability, or major injury to personnel.” For intuitive reasons, they trace from Critical Safety Items, which are items that contain “a characteristic which failure, malfunction, or absence of could cause a catastrophic or critical failure resulting in the loss or serious damage to the aircraft or weapon system, an unacceptable risk of personal injury or loss of life, or an un-commanded engine shutdown that jeopardizes safety.” From a product variation point of view, CCs can be logically viewed as a special kind of KC in that the consequence of functional degradation (caused by variation from the nominal value) is that personnel safety is compromised.[30] Therefore, in order to simplify the narrative and diagrams, whenever KC is used in this appendix, it should be interpreted to include the special subset of KCs that are CCs.

B.1.3 Key manufacturing process defined

According to SAE AS6500, a Key Manufacturing Process (KMP) is “a process that creates or substantially affects a key characteristic”, while a Critical Manufacturing Process (CMP) is “a process that creates or substantially affects a critical characteristic.” In order to simplify the narrative and diagrams, whenever KMP is used in this appendix, it should be interpreted to include the special subset of KMPs that are CMPs.

B.1.4 KC, CC, and KMP relationship

The relationship between KCs, CCs, and KMPs/CMPs are illustrated in Figure 19.

[30] This guide adopts the SAE standard definitions for key and critical characteristics. There are other definitions published in DoD and aviation literature. As defined in DOD-STD-2101 (Classification of Characteristics), a Critical Characteristic is one that “*analysis indicates is likely, if defective, to create or increase a hazard to human safety, or to result in failure of a weapon system or major system to perform a required mission.*” Per the Aviation Critical Safety Item Management Handbook, Critical Characteristics identified on Critical Safety Items (CSI) must undergo 100% inspection unless the government has approved a sampling or Statistical Process Control approach. In addition to aviation CSIs, NAVSEA Instruction 9078.1 defines CSIs for naval ships as any ship part, assembly, or support equipment containing a critical characteristic whose failure, malfunction, or absence may cause a catastrophic or critical failure resulting in loss or serious damage to the ship, or unacceptable risk of personal injury or loss of life. The NAVSEA instruction also requires stringent quality controls on CSIs. Elements of these definitions are present in SAE AS6500, with slight variations. While distinctions might be made in these definitions ***between*** key and critical characteristics, the set of key and critical characteristics, and the requirements for control of them, is ***in the aggregate*** consistent. The guidance herein is therefore considered in harmony, rather than in conflict, with these definitions.

Appendix B
Key and Critical Characteristics

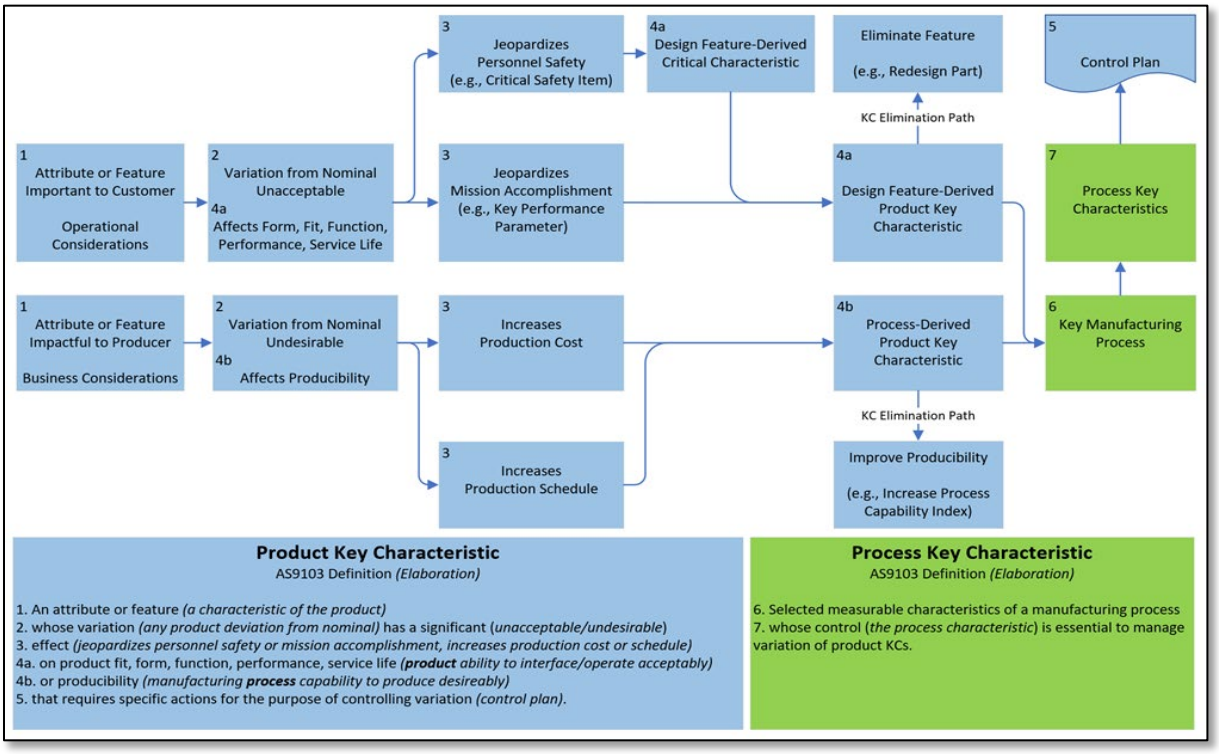


Figure 19: KC, CC, and KMP relationship

B.1.5 KC identification

It should be clear from their definitions that KCs are attributes of the product whose tolerances must be tightly controlled to ensure mission accomplishment and safe operation. Achievement of highly capable processes is a desired output of the KC identification and management process, not an input to it. KCs derived from operational considerations (mission success, human safety) cannot be eliminated simply because processes have been developed that are highly capable; the product key characteristic whose variation significantly affects mission completion or human safety must therefore either be eliminated or controlled. Management (for example, process control plans and process improvements efforts) of these operationally derived KCs may take process capability into consideration when selecting control actions in the Control Plan, identification of them as KCs may not. This is because KC identification provides desirable benefits beyond those gained on a single contractor's factory floor, as shown in Figure 20.

- Identifies product characteristics for which manufacturing process capabilities must be assessed and carefully managed.
  - Those that will require rigorous process controls, e.g., SPC techniques
  - Those that would be candidates for process variability reduction activities.
- Identifies product characteristics that may benefit from redesign
  - Eliminate the KC
  - Achieve a more robust design (e.g., permits manufacture using more capable processes).
- Facilitates communication among design and manufacturing engineers by linking the competing objectives of performance and producibility together in a common point of reference on the part or system.
  - Many KCs are interface characteristics; their clear identification on drawings enhances communication between engineering and manufacturing as well as among prime contractors and suppliers.
  - Encourages selection of suppliers with process control practices in place for key and critical characteristics.

Figure 20: Benefits of KC identification

B.1.6 KC elimination principles

Figure 19 addresses a common question regarding KCs: “Can we make a KC go away? The answer depends on which kind of KC is being questioned. If it means Design Feature-Derived Product KC, which includes those derived from Critical Characteristics (see boxes labeled “4a” in Figure 19), that trace to functions identified by the customer as mission essential or safety-related, then the answer is likely “no” unless the feature can be eliminated by redesign. In this circumstance, the capability of a process is not a factor in designating a product characteristic as “key” because the designation also serves as an important communication purpose to other potential producers (for example, re-competed parts produced by new suppliers, spare parts produced by government depots). The selection and use of highly capable processes reduces the data collection, monitoring, and management attention required, but it does not eliminate the KC designation if the feature whose variation from nominal influences human safety or mission accomplishment remains part of the design. If, on the other hand, the question refers to Process-Derived Product KCs, or features identified by the contractor’s design team as KC’s due to a less than desirable process capability, the answer is “possibly”. If the design feature can be eliminated, or if the contractor’s process capability can be improved to an acceptable level, the contractor may conclude that the designation of key for business reasons is no longer desirable or necessary. These concepts are summarized in Table 43.

Appendix B
Key and Critical Characteristics

Table 43: Properties of Key Characteristics

Type:	Design Feature-Derived Product KC	Process-Derived Product KC
Definition	Attribute or feature whose variation has a significant influence on product fit, form function, performance, and/or service life. Includes KCs of type CC, which are attributes or features whose variation has a significant impact on human safety or could cause a catastrophic failure resulting in loss of life, permanent disability, or major injury to personnel.	Attribute or feature whose variation has a significant influence on producibility, thereby impacting production cost or schedule.
Motivator	Optimize product to satisfy customer expectations	Optimize processes to address business considerations (for example, efficiently use resources, reduce Cost of Quality)
Can we make them go away?	Yes, if the product design can be modified to eliminate the key attribute/feature. This is not always possible, particularly for non-dimensional attributes/features (for example, surface finish, strength, hardness). Additionally, the attribute/feature must be eliminated, not mitigated. Even for dimensional features, the action taken to "eliminate" the KC must be carefully examined. For example, tightening a dimensional tolerance changes the production processing requirement (the feature is controlled/mitigated), not the product feature itself (which is not eliminated). As long as the attribute/feature remains, its designation as key remains. The key designation is because product deviation needs to be controlled and communicated, even if the manufacturing process producing it is capable.	Yes, if the contractor can make the part more producible by eliminating the design feature/process capability mismatch, either by modifying the product design to reflect available process capabilities or satisfying design features using improved processes that are statistically stable and capable. According to SAE AS9103B, "*The process shall be statistically stable and capable (that is, with Cpk > 1.33) or as defined by or agreed with the customer*." See Section 5.5.4.2 for more insight into the process capability index represented as C_{pk}.

Appendix B
Key and Critical Characteristics

Table 43: Properties of Key Characteristics

Type:	Design Feature-Derived Product KC	Process-Derived Product KC
Rationale	Product variation from nominal introduces safety or mission jeopardizing concerns is what makes the feature key, not that the process producing it possesses a lower than desirable C_{pk}. Furthermore, feature-derived Product KCs serve as an important communication tool to other producers of key features; the continued designation of an attribute or feature as key communicates the criticality of the feature to new producers (for example, subcontractors, DoD MRO depots). The feature will always be important to control closely and communicate clearly, even if a particular producer has mastered its production. If available processes are highly capable of producing Product KCs (including those derived from CCs), the Process Control Plan may be adjusted, for example, to reduce inspections.	Variation from nominal is caused by lower than desired C_{pk}, increasing the C_{pk} to an acceptable level can make them go away. Since Process-Derived Product KCs are identified by the producer, they can be eliminated by the producer if undesirable cost and schedule effect risks are satisfactorily mitigated and there is no need to continue communicating the feature as key to new producers (that is, because the acceptable level of process capability has become ubiquitous in the industry.)

Appendix C
Manufacturing Operations Management

C.1. SCOPE

This section provides details to consider when determining the best methods for managing manufacturing operations. These include challenges to planning and controlling material requirements and theories in addressing these challenges.

C.2. PUSH-BASED PRODUCTION SCHEDULING AND CONTROL SYSTEMS

In push-based production scheduling and control systems, the trigger for releasing raw materials and parts to the factory floor for processing is a forecasted need date, backward passed through the series of production steps. In production facilities producing a large variety of end-products, planning and controlling production can quickly involve a very complex network of decisions and actions beyond the capability of most human minds to handle unaided. Automated systems have therefore been developed over time to help analyze and manage all the data needed to support push-based production scheduling and control decision-making.

C.2.1. Material Requirements Planning

Earlier systems, dubbed Material Requirements Planning (MRP), handled the backward pass calculations by combining forecasted need dates with information extracted from a product's indentured Bill of Materials (BOM). Using planned need dates and established processing times (perhaps based on labor standards), production schedules and purchasing plans were created. Once the calendar reached lead-time away from forecasted need, triggers caused orders to be released and/or production to begin on the longest lead items, kicking off the web of production processes necessary to complete the scheduled batch of end-products. A production control module within MRP captured and reported on progress against the plan. When deviations from the plan were detected, expediters engaged with floor supervisors to influence course corrections.

C.2.2. MRP challenges and shortcomings

One of the early challenges not handled well by MRP was production resource constraint management. MRP systems frequently failed to produce executable plans because they did not accurately limit planned production requirements to available human and machine process capacity. In fact, earliest MRP systems did not even pretend to account for limits to capacity, simply assuming infinite capacity during the backward pass calculations. This shortcoming became quickly and painfully evident as WIP inventory built up behind constraining resources; even expediters, in extreme cases, were at a loss as to how to correct this problem. Eliyahu Goldratt's book, *The Goal*, vividly describes this phenomenon using a novel approach (pun intended). Mr. Goldratt illustrated Mr. Ohno's recognition that an effective production scheduling and control system must anticipate and account for the constraining resource to ensure flow is an outgrowth of this phenomenon. Optimization initiatives should focus then on fully utilizing bottleneck operations efficiently since utilization and efficiency improvements in non-bottleneck operations have ultimately no effect on a production system's ability to deliver end-items. Increased utilization at non-pacing operations just produces WIP with no place to go. Local overproduction, therefore, even if it results in high productivity for that work center, results in excess WIP, which is waste. Production managers, suddenly heavily invested in WIP inventory rather than profit generating final products, find themselves in a sea of despair; parts, parts everywhere, but not a finished good to sell.

Appendix C
Manufacturing Operations Management

C.2.3. Manufacturing Resource Planning

Eventually rough-cut capacity planning, including the ability to evaluate down-stream effects of different demand scenarios, was incorporated into MRP systems, resulting in a new and improved production planning and control system dubbed “MRP II”. Since it was considered a more all-encompassing planning system, and perhaps to distance itself a bit from its less effective predecessor, MRP II was re-branded Manufacturing Resource Planning. Note that the name change redirects emphasis toward the broader manufacturing resources rather than just the material requirements being planned. This iteration of production planning and control software tools possessed staying power and continues to this day[31].

C.2.4. MRP II benefits

The benefit of push-based production scheduling and control systems is that customer demand (or at least some portion of it) can be quickly satisfied from available inventory stores since production anticipates future demand. MRP II systems, however, suffer from (1) a level of complexity that many find unappealing and (2) the possibility that inaccurate forecasts will drive production of finished goods in excess of, or insufficient to meet, actual customer demand.

C.3. PULL-BASED PRODUCTION SCHEDULING AND CONTROL SYSTEMS

In certain situations, the advantages of push-based production scheduling and control can become a liability. The scope of liabilities become clear by asking one simple question about the demand forecasts driving every decision being made on a forecast-driven production floor: what if the forecasts are wrong? Taiichi Ohno gave this question a lot of thought and concluded that the answer can be wrapped up in a single word: waste. Wasted effort producing and storing product for which demand has waned. Wasted time spent sidestepping or tripping over WIP that is spilling into aisleways. Wasted investment opportunities that were squandered on parts, some ultimately unwanted, waiting in factories and warehouses to be processed.

C.3.1. Addressing waste caused by push-based systems

In his quest to eliminate as much waste as possible (that is, to become lean), Mr. Ohno advocated concepts of production material planning and flow that turned traditional, push-based production planning and control methods almost completely upside down. His “lean” system: (1) specified what adds value from a customer’s perspective; (2) identified the steps that produce customer value and eliminated those that do not; (3) ensured those steps were unimpeded by, for example, interruptions, detours, waiting, and scrap/rework/repair; and (4) triggered production actions by pulling only what was demanded by the customer just in time. This all may, admittedly, be easier said than done due to the necessary, complex, symbiotic connection that exists among the many best practices demanded by the approach. As an illustration, consider the interrelationships presented in the following paragraph:

> A production environment that attempts to be lean strives to have minimal work in process. In order for this to occur, ideally the production is **pulled** through the production processes rather than pushed (note how much easier it is to keep a rope straight when it is pulled rather than pushed). This requires close coordination with customers to develop a

[31] When broader business functions (for example, finance, sales, product support) are incorporated into a system of systems (usually implemented as a collection of “modules”), the result is an Enterprise Resource Planning (ERP) system, which is beyond the scope of this Manufacturing Management Program Guide. Nonetheless, the MRP II modules remain as modules within a broader ERP, tied in a more integrated fashion to additional enterprise business functions.

production plan based on *demand* rather than forecasts. In such a lean production environment, operating on the basis of **just-in-time** deliveries (either from an external supplier or an internal up-stream process), one bad part can shut down the line since the operator cannot simply set the bad part aside and grab another part off the "pile". Lean production lines, therefore, by their nature, do not have large quantities of extra parts lying around, which means the few parts that are available need to be of **high quality**. This drives the need for a **defect detection and/or prevention** mechanism capable of ensuring only quality products proceed to the next production phase (for example, through effective quality inspections) or, better yet, only quality products are produced to begin with (for example, using SPC to prevent defects). But SPC is only as good as the actions taken when an out-of-control process is detected. This means the operators on the shop floor should be *empowered* to take the appropriate action instead of fearful of the consequences if they pause production.

Notice the bold words in the preceding paragraph depend on each other for benefits to be realized. For example, SPC without empowerment can result in employee frustration as identified issues get ignored and line stoppages ensue when defective parts get passed just in time to be a problem for downstream operations. The pull-based production *scheduling* driver then, is customer orders. Since the trigger is at the end of the line (where production is "pulled" by the customer), rather than the beginning (where production is "pushed" by the forecast), production *control* is handled in a lean production environment by employing two fundamental concepts that may be used individually or together: takt time and kanban.

C.3.2. Takt time: pull-based production control through synchronization.

At some point near the end of production, a collection of fabricated and/or purchased parts and subassemblies merge into a final assembly series of operations. A lean final assembly line, which is a sequence of dependent product build processes, is controlled by takt time. Takt time "*precisely synchronizes the rate of production to the rate of sales to customers*.[32]" Takt control works most efficiently when serially arranged processing steps are conscientiously aggregated into increments of work with roughly equal durations. Customer orders are used to calculate the timing of WIP movement (takt time) by dividing a product's overall lead time by the number of steps necessary to produce it. For example, if the customer demands 20 aircraft per year, and the factory operates 200 workdays per year, then the takt time is 200 ÷ 20 = 10 workdays. Every ten days, a completed aircraft must exit the production line (yielding 20 aircraft over the span of a year) and every prior subassembly must move forward one process step. In this way, every step in a lean, pull-based serial production process moves material (passes its finished goods to the next step and receives finished goods from the prior step) according to a perfectly synchronized schedule based on this calculated takt time. If demand increases, takt time must reduce; if demand decreases; takt time must increase. This synchronized material movement approach, in an environment that allows a measure of product configuration variety, approximates, without perfectly mimicking, a moving production line. In this way, Taiichi Ohno generalized for product lines possessing configuration variety (that is, the synchronized final assembly line) Henry Ford's productivity special case for production lines with no variety (that is, the moving final assembly line).

[32] Womack, J. and Jones, D. (1996). Lean Thinking. Simon & Schuster. p. 55.

C.3.3. Kanban: pull-based production control through signaling

Lean production based on customer demand can also be controlled when the processes are arranged on the shop floor in a less serially organized manner (that is, when process steps do not yet line up pleasingly and synchronization is therefore less straight-forward). In such an environment, control of WIP movement is maintained by using “kanban” signals. Kanban, most literally translated, is a “card” that regulates movement of processed goods. Kanban rules dictate that a completed “batch” of parts may not be sent to the receiving, downstream process until that receiving process indicates (by sending a kanban/card) its readiness to receive the parts. Over time, a variety of more creative methods to signal release of WIP have been introduced (for example, empty bins, visual signals/flags, marked/empty space on the floor of receiving processes clearly visible to feeding processes), but “kanban” remains as the term representing this conceptualization of production control. Regardless of the specific implementation details, all kanban systems prevent material from being “pushed” down the line; material can only be “pulled” from succeeding operations when that operation signals (via kanban) that it is ready for it.

C.3.4. Synchronization and signaling can be complementary tools

These two pull-based production control concepts are complementary; takt time essentially takes advantage of the kanban signaling technique as well. In takt-controlled final assembly, no succeeding process step accepts new work until the floorspace (in this scenario, the kanban) needed for that assembly step is available (that is, is empty). In takt-based control, nothing moves forward (that is, is pushed) before its time; availability of the succeeding process steps, and the signal for material movement, simply happen for each process step at precisely the same time.

C.4. FACTORS INFLUENCING SELECTION OF PUSH VS PULL PRODUCTION PLANNING AND CONTROL SYSTEMS

Push-based scheduling and control may be preferable if product demand requires, or competitor capabilities provide, immediate customer demand fulfillment. However, when customer demand can be accurately forecasted or influenced, pull-based production scheduling and control has striking advantages. Effectively implemented, pull-based production scheduling and control systems promise significant reductions in (1) wasted time, (2) unnecessary effort, and (3) suboptimal capital investment. *Admittedly*, the products purchased by the DoD can be very different from products produced for commercial customers; however, the very nature of much of DoD demand, which is specified by the customer up front in a contract, makes it fertile ground for considering lean production scheduling and control practices.

Appendix D
Manufacturing Surveillance

D.1 SCOPE

This section provides methods of collecting data and measuring the success of the MM Program.

D.2 SURVEYING MANUFACTURING EFFECTIVENESS

Surveillance of manufacturing execution effectiveness boils down to capturing and analyzing the ability of the production process to produce customer-pleasing, design-conforming products, which is to say that any survey of manufacturing effectiveness needs to assess both measures of performance (customer delight) and measures of conformance (production/quality manager delight).

D.2.1 Measures of performance

Collection of data reflecting whether the product meets customer expectations often comes in the form of customer surveys. Many contractors have instituted initial customer satisfaction data programs that gather feedback shortly after product delivery. Quality escapes found during receiving inspection are fed back to the contractor for root cause and corrective action on the plant floor to prevent recurrence.

D.2.2 Measures of conformance

Collection of data reflecting whether the product meets production and quality manager expectations comes directly from the plant floor. A nonconformance, which is often used somewhat euphemistically in place of the term “defect”, represents a failure of the production system to produce the product right the first time. When the nonconformance is caught by its producer, it is reworked, repaired, or scrapped/replaced. Reworked items, after being reworked, conform to the design and will therefore perform as intended. Repaired items do not conform to the design specifications but have been deemed acceptable to the customer through a formal approval process; these items will perform largely, if not precisely, as intended despite their deviation from the design specification. Some repair methods are standardized as customer pre-approved Standard Repair Procedures (SRP) to expedite dispositioning. Scrapped items neither conform nor have the potential to perform acceptably and should be discarded. The aggregation of Scrap, Rework, and Repair (SRR) effort as a proportion of total production effort represents the rate of nonconformance and is often expressed as a percent defective. All three defect dispositions have costs associated with them (that is, defect correction, mitigation, or disposal); when the SRR rate is translated into dollars, the metric is called Cost of Rework, Repair, and Scrap (CORRS). With the emphasis on capturing, quantifying, and tracking SRR and CORRS, it is important guard against complacency. Resist developing a measure of “tolerance” for poor quality, accepting non-conformances as unavoidable due to military system complexity and relatively low production rates. Failing to do so will likely result in primary emphasis being placed on detecting and dispositioning defects rather than on preventing defects in the first place.

D.2.3 Cost of Quality

Figure 21 illustrates the importance of considering the cost of producing nonconforming product rather than merely its rate of occurrence. The top chart indicates the incidence rate and disposition for each type of defect. The total SRR rate for the reporting period (the sum of all the individual rates) is 25.8%. Scratches have the highest incidence of all defect types; at 7.5%, nearly double that of the nearest competitor. Way down in fifth place is “too short” signifying the part was cut beyond what the specification allowed. Notice defect types that allow for rework in

the form of a second cut (for example, “too long”, “too wide”, and “too thick”) all have a higher incidence but allow for reworking of the part. Defect types that cannot be corrected by a second cut (for example, “too short”, “too narrow”, and “too thin”) must be scrapped, which is a much costlier proposition when these defect types occur. Even though scratches, the lone repair opportunity in the group, have the highest incidence, they can be inexpensively sanded and touched up according to an approved SRP. The cost of scratch repair is therefore far outpaced by the cost of scrapping parts that have been cut too short, too narrow, or too thin.

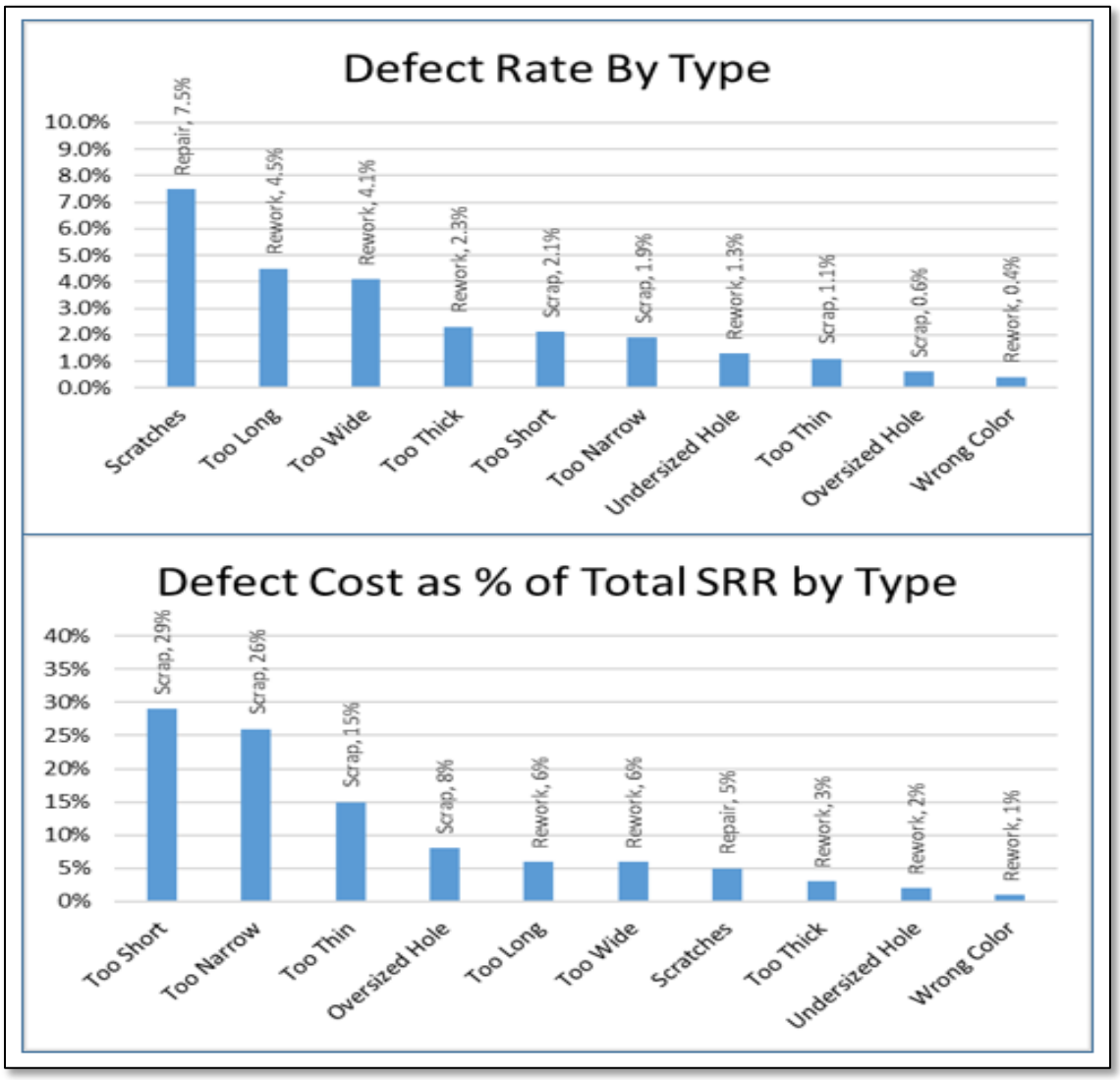


Figure 21: SRR Rate vs CORRS view of defects

Appendix D
Manufacturing Surveillance

D.2.3.1.1 Quality Escapes

The preceding discussion, with its focus on defect detection and correction before product delivery highlights what happens when a quality *surveillance* system is performing its intended purpose; that is, it is capturing defects before they depart the confines of the production process and find their way to the customer. When a nonconformance slips past its producer unnoticed and is later discovered by the customer (whether it be a down-stream process or an end-user), the nonconformance becomes a special kind of nonconformance called an “escape”. Escapes carry with them a far greater cost consequences than factory-constrained CORRS; they trigger costs associated with warranty, packaging, transportation, customer service/retention/goodwill, and in extreme cases, legal action. And the costs discussed so far only scratch the surface since they all focus on the costs associated with quality failure.

D.2.3.1.2 The true cost of quality

The total Cost of Quality (CoQ) considers quality cost factors beyond the cost of failing to conform to design specifications, to include “above the shop floor” costs associated with defect prevention and quality appraisal activities. CoQ, then, is defined by the American Society for Quality (ASQ) as the sum of failure costs, appraisal costs, and prevention costs as illustrated in Figure 22.

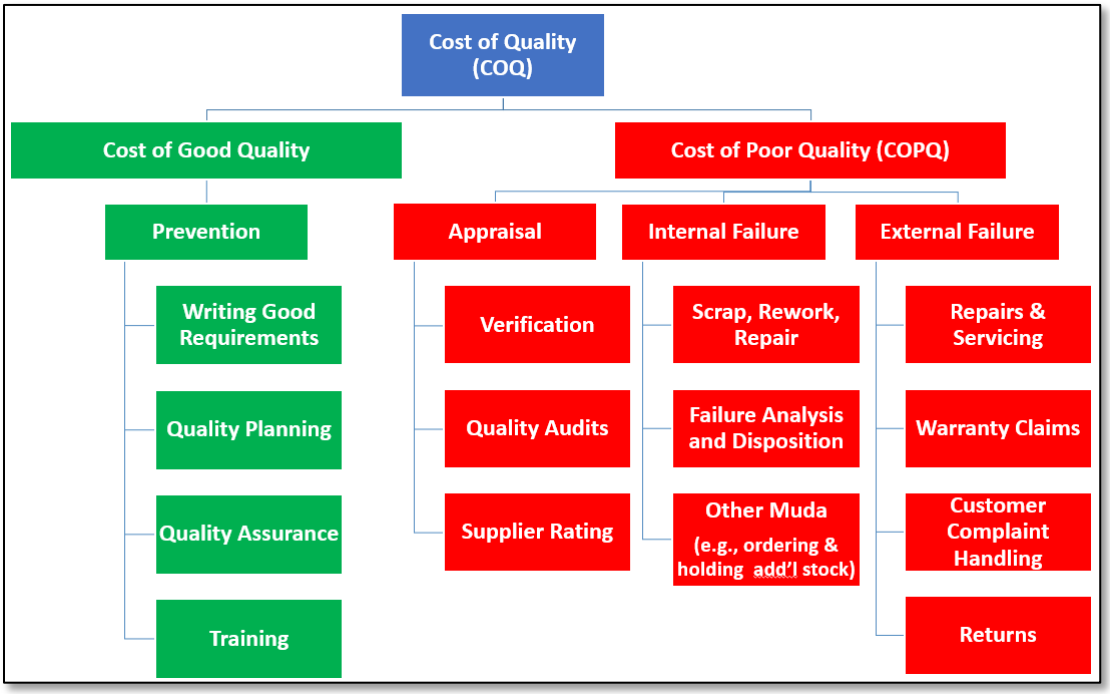


Figure 22: Cost of Quality

Clearly, every activity and cost category associated with non-conformance is waste that contributes to the total COQ (for example, direct charges, indirect charges, G&A, overhead, profit associated with non-conformances). Even the very existence of some entire organizational elements would be unnecessary if it were not for non-conformances. CoQ, therefore, highlights the difference between the actual cost of a product or service and the reduced cost of the same product or service if there was no possibility of substandard service, product failure, or manufacturing defects. The broad category of “other muda” asserts that even the cost

associated with forklift drivers unloading replacement material is part of the cost of quality. For perspective, experience indicates CoQ ranges from three to six times greater than CORRS alone. Capturing and analyzing all contributors to CoQ provides a clearer understanding the full impact of quality failures, providing strong reinforcement of the need for a prevention-based quality culture.

D.2.3.1.3 Examples of quality costs

Table 44 provides examples (not all-inclusive) of prevention, appraisal, and failure costs.

Table 44: Examples of quality costs

Costs	Description	Examples
Prevention Costs	Costs related to efforts to prevent the occurrence of non-conformance and poor quality in products or services.	• Quality Training & Education • Quality Planning • Process Control Monitoring • Process Capability Evaluations • Process Validation • Process Mistake-Proofing (Poka-Yoke) • Design Reviews • Supplier Reviews • Quality Improvement Activities
Appraisal Costs	Costs associated with measuring, evaluating, auditing, and controlling operations to ensure conformance to quality standards and requirements.	• Inspection • Quality Audits • Metrology • Supplier Certifications • Testing • Review of Inspection & Test Results • Other Costs Associated with Evaluation of End Products
Failure Costs	Costs related to efforts to correct the occurrence of non-conformance and poor quality in products or services.	• Internal (Prior to Delivery) • Cost or Repair, Rework & Scrap • Material Review Board Costs • Expediting & Liaison Engineering • Process Capability Evaluations • Troubleshooting, Retest, Re-Inspection • Re-procurement • External (After Delivery) • Processing Complaints & Warranties • Shipping & Handling • Follow-on Repair or Retrofit • Liabilities and Penalties

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D.2.3.1.4 The continuous pursuit of defect prevention

Not every CoQ element may be, or even should be (for example, prevention costs), fully eliminated; however, an effective quality program will shift focus from detection and correction of failures to prevention of them and drive systematic process improvements that yield overall CoQ reductions. Figure 23 illustrates notional CoQ shifts and reductions expected over time when pursuing continuous process improvement.

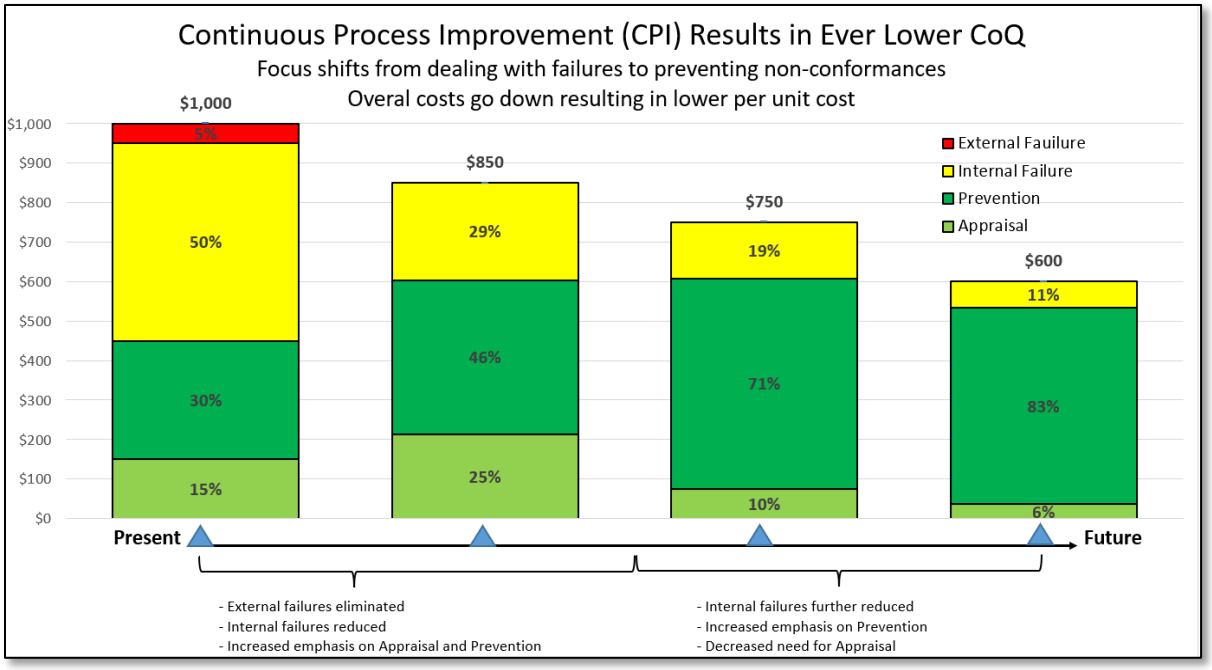

Figure 23: Notional CoQ shifts over time

The result of a prevention-based quality culture will be more affordable products, delivered in a timelier manner, with improved inherent quality and reliability. Those who say that the quality of our delivered products is high are right. The reason for pursuing CoQ is because we want to know how the high levels of quality were achieved. It is usually faster, better and cheaper to build it right the first time.

D.2.3.2 Surveying Manufacturing Efficiency

Before launching into a discussion of surveying manufacturing efficiency it is important to level the playing field by defining some important terms and describing typical production floor behavior. The time it *should take* to produce a product or service is called “standard”. The time it *did take* to produce a product or service is called “actual”. The time between should take (standard) and did take (actual) is inefficiency. The ratio of Standard to Actual is called “efficiency”; rates below 1.0 (or 100%) indicate the presence of inefficiency. The ratio of Actual to Standard is called realization, a unitless factor (often referred to as a realization factor (RF)).

D.2.3.3 Labor standards and operational efficiency are not stagnant

In a production environment, neither standards nor inefficiency remain constant (refer again to Figure 16). Standards can be increased when scope is added and reduced when methods improvements are implemented. Inefficiency may increase for a variety of reasons, but typically drops gradually over time as the production system “learns” the tasks necessary to accomplish production. Figure 16 also hints at why many prefer the term “improvement curve” over “learning curve” since many of the elements impacting the curve have nothing to do directly with human learning. For the purposes of this discussion, however, “learning curve” will be used to describe the effect all these factors have on the ability of an enterprise to produce product.

D.2.3.4 Learning theory

In spite of the desire by many analysts to believe it possesses unsurpassed powers of precise prognostication, learning curve theory is an observed phenomenon that reasonably predicts human-driven performance (for example, in a production environment) over time. It is an imperfect art (that is, predicting human behavior) upon which precise statistical techniques (for example, regression analysis) has been thrust. While it may not be perfect, learning theory has been accepted and used throughout industry as a relatively accurate way to project an efficiency improvement path toward the ideal: production accomplished in the amount of time it should take to accomplish it. No idle time, no scrap or rework, no tooling problems, no inefficiency caused by an untrained workforce. Just pure, unadulterated production perfection. Upon arriving at this elusive destination, inefficiency is zero, actual = standard, and the realization factor = 1.

D.2.3.4.1 Determining an appropriate learning rate to use for projection

Though the tools and techniques available to evaluate and project learning in a production environment have evolved over time, the premise has always been the same. Determine and then use the best-fitting learning curve to predict the future. If data is not available, or until it becomes available, benchmarking (that is, using industry averages) is customarily used to determine an appropriate learning rate. When specific production program data becomes available, statistical techniques (that is, employing an exponential form of regression) are used to determine the actual learning rate. Both approaches (benchmarking and statistical analysis) assume past comparable performance is a reasonable predictor of future performance. This assumption, given necessary conditions addressed later, is backed by many years of empirical evidence. Of course, it is still appropriate to question actual measured experience when it is markedly different from industry averages.

D.2.3.4.2 Learning theory tools

Since learning theory suggests improvement is not linear (improvement occurs with each doubling, rather than each unit, of production), performing manual calculations and plotting of trends can be tedious. Before personal computers and statistical analysis software became ubiquitous, computational simplification was accomplished by projecting lots instead of units and/or using cumulative learning curves (that is, Crawford cumulative average curves) rather than unit learning curves (that is, Wright’s original unit curves). Graphical simplification was accomplished by plotting learning theory’s exponential relationship on log/log graph paper. There is nothing inherently better or worse associated with using any of these techniques in terms of their predictive capability. More recently, desktop applications (for example, Microsoft® Excel) possess built-in regression tools, including the regression style used by learning theorists (that is, “power regression” in the form of $y = ax^b$). Using such automated statistical analysis tools, when sufficient actual data is available, the best-fitting “power” regression curve (or

learning curve) can be easily determined and plotted. As with any form of regression, correlation coefficients provide the measure of confidence inherent in the best-fitting curve.

D.2.3.4.3 Interpreting learning curve data

Since contractors essentially use the same data, tools, and techniques to accomplish labor analysis and projections, differences of opinion regarding the path of continuous improvement are mostly based on philosophical rather than analytical grounds. The philosophical questions revolve around whether or not past performance accurately and reasonably represents what is to be expected in the future. The questions exist and must be entertained because experts agree that *learning theory applied to historical actual data has limits*. It turns out the observed phenomenon known as learning theory only reasonably predicts human performance if certain conditions persist. The most ideal environment for learning theory (that is, natural continuous efficiency improvement) to thrive is one in which the product is stable, the processes and workforce are stable, and demand for the product (or other similar products) gradually increases to fill the workload void created by improved efficiency. Product instability, process instability, workforce instability, and demand fluctuations all put upward pressure on the learning curve. Most of these factors result in temporary deviations from the historical trend. Over time, a variety of techniques have been developed to address such “loss of learning” conditions. In contrast to environmental conditions that negatively influence learning, *methods and operational improvement initiatives can place downward pressure on the learning curve*. Whether ultimately for good or for bad, when any of these situations are anticipated in the course of upcoming production, tweaking of the pure learning curve projection technique is necessary to account for atypical learning environments. It is not uncommon to have both upward and downward pressures on the learning curve to coexist. In the end, leaning theory asserts that manufacturing efficiency improvement occurs naturally and should be expected unless impeded, whether or not intelligently designed process improvement initiatives are also pursued.

D.2.3.5 The negative effect of Parkinson’s Law on efficiency improvement, illustrated

Consider the phenomenon illustrated in Figure 24.

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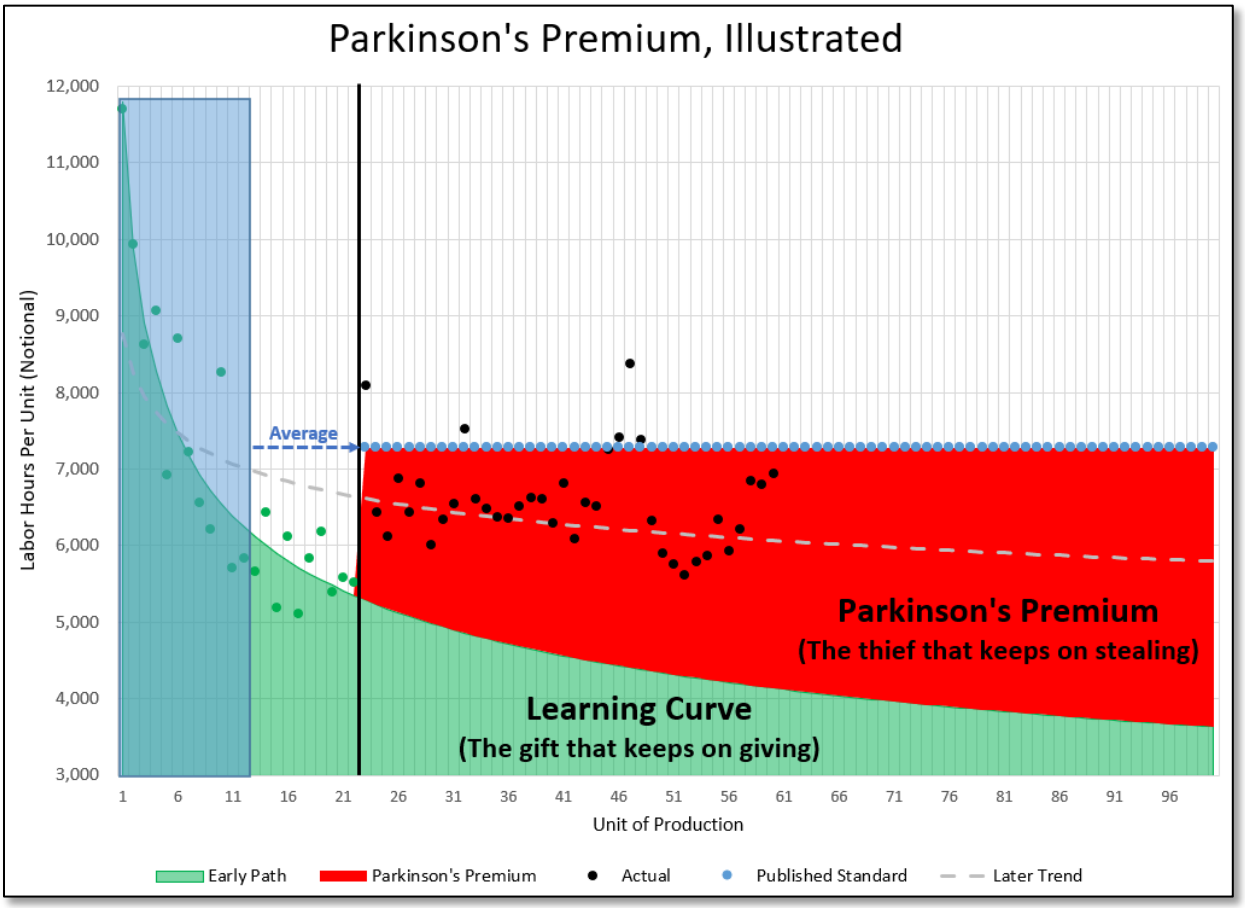

Figure 24: The negative effect of Parkinson's Law on efficiency

The essence of Parkinson's Law is that work will expand to fill available time[33]. Notice in Figure 24[34] the impact of learning as it aggressively chips away at the labor hours necessary to produce the first 22 units of production. Notice also as the first 22 units wrapped up, an "allowable" standard was published based on the average of very early experience (approximately the first dozen units). Even though performance had already improved beyond this published, allowed standard, Parkinson's Law's effect was instantaneous. Observe several brief periods afterward when Learning Theory valiantly battled back (notice units 36 and 52), only to subsequently concede defeat over and over to the more powerful opposing force of this persistent foe. The red space between what is possible (learning theory's early path) and what is allowable (the published standard) represents the potential loss of what should have been simply attainable efficiency. The actuals after unit 22 indicate how much of that lost potential actually occurred; the "later trend" line indicates the projection of how much of Parkinson's premium will be realized in the future based on the subsequent, less aggressive later trend. Contractors need to actively battle this tendency (that is, allowing past poor performance to influence future expectations) lest the projections of efficiency become a cycle of self-fulfilling,

[33] Named for Cyril Northcote Parkinson, a British historian who observed this phenomenon in bureaucracies and published the first version of this axiom, and others, in Parkinson's Law or the Pursuit of Progress in 1958.
[34] The data in Figure 24 is notional, but the concept illustrated is very real.

objectionable prophecies of increasingly inefficient futures. Yes, the last sentence was stated correctly; there have been observed instances in which the pull of Parkinson's law was so powerful it actually reversed the course of learning into "negative learning" territory, bending the curve away from what is possible back toward what is allowable. Parkinson's premium robs contractors of future profits and taxpayers of future savings. If continuous process efficiency improvement is the gift that keeps on giving, Parkinson's premium is the thief that keeps on stealing.

Appendix E
Continuous Improvement

E.1 SCOPE

This section provides details to consider when adjusting activities to improve the manufacturing process.

E.2 PROCESS CONTINUOUS IMPROVEMENT THROUGH PROCESS VARIATION CONTROL AND REDUCTION

E.2.1 Process Variation Basics

Process variation has both special and common causes; understanding the nature of variation specific to a given process is necessary to correctly identify and control sources of variation. Special cause variation is variation that is not inherent to a process, is due to some outside (often controllable) influence, and is usually detected by its predictable, nonrandom frequency (for example, variation introduced by tooling, machine programming, drill bit wear). Common cause variation is the that which is inherent in the process; it is the variation that remains after all special causes have been eliminated. There are categorically two types of manufacturing process improvements: (1) those that transform out-of-control processes into in-control process (that is, they eliminate assignable causes of variation), and (2) those that decrease process variation around/from the desired nominal value (that is, they address common causes of variation).

E.2.1.1 Process Improvement Step 1: Reigning in rogue conditions

The first process improvement objective is to detect and eliminate any reason a process fails to live up to its potential. There are a variety of statistically detectable “rogue” conditions that should trigger investigations into an assignable cause. Recognized by some as the “Western Electric Rules”, they are as described below and illustrated in Figure 25:

1. Any points falling outside the established control limits
2. Seven consecutive points on one side of the average/center line
3. Six consecutive points steadily increasing or decreasing
4. Fourteen points alternating up and down
5. Two out of three consecutive points in the outer third of the control region (for example, in the region between 2 standard deviations and 3 deviations)
6. Fifteen consecutive points within the center third of the control region (that is, in the region between -1 standard deviations from the center line and +1 standard deviations from the center line).
7. Eight consecutive points greater than one standard deviation from the center line with none falling in the center third of the control region.

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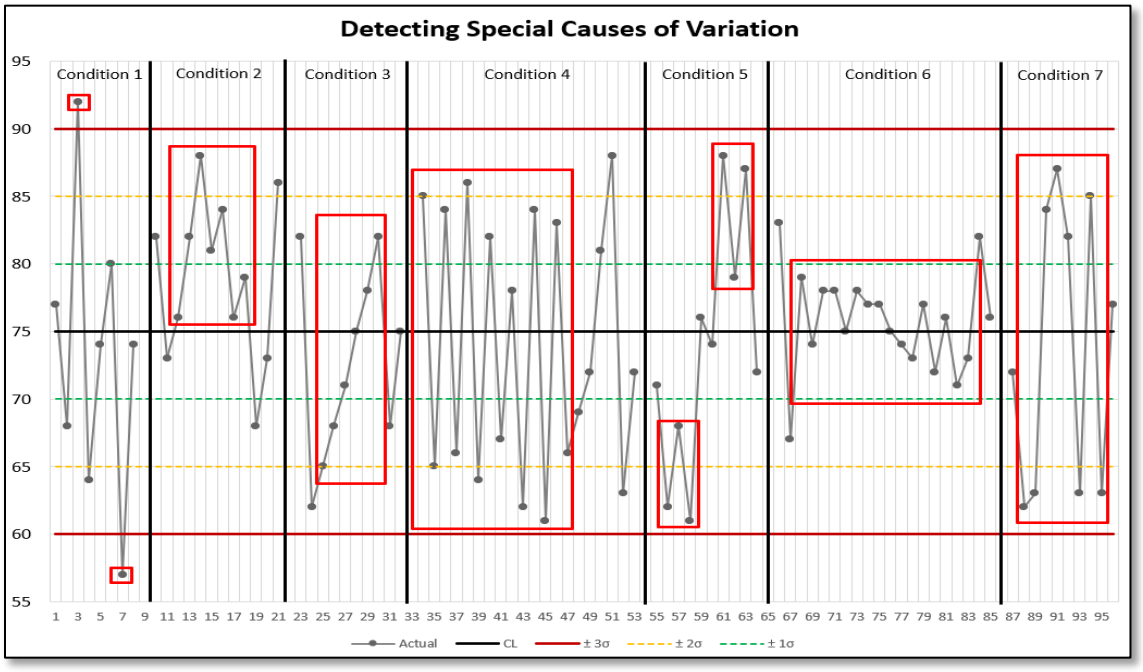

Figure 25: Special causes of variation illustrated

It is important to note that these special causes have an external source; elimination of the special causes will free the process to perform as it is designed/intended/capable. But what if the way the process is designed/intended/capable is not good enough? When external factors impacting the process performance have been eliminated, internal process limitations can be addressed.

E.2.1.1.1 Process Improvement Step 2: Zeroing in on ideal conditions

There are two ways to improve in-control processes by addressing conditions inherent within the process itself: (1) improve the process such that it produces product features closer to the designed nominal targets, and (2) improve the process such that it does so consistently (that is, the amount of variation from that target that is inherent in the process is reduced). These two steps are appropriate whether attempting to improve measures of effectiveness or measures of efficiency. Examples of each are provided in the sections that follow.

E.2.1.2 Continuous process effectiveness improvement, illustrated

Process effectiveness, which influences how well the product satisfies the customer, benefits from continuous improvement efforts. To illustrate the point, consider the following scenario:

The DoD is interested in purchasing rulers for their acquisition workforce. A specification has been written describing the requirements as follows:

- Length: 12 inches, plus or minus one inch
- Width: 1 inch, plus or minus ½ inch
- Thickness: 1/8 inch, plus or minus 1/16th inch

The DoD has further specified ruler length as a key performance parameter, and the contractor has determined to therefore identify the length dimension as a key characteristic. Since it is a key characteristic, the contractor has developed a process control plan to

monitor and improve the process that cuts the rulers to length.

E.2.1.2.1 Process effectiveness improvement step 1: get it under control

After capturing data for 22 batches, the contractor noticed the process operating in an out-of-control manner. 1 shows batch average lengths during periods one through 22 falling outside the expected process control limits on two different occasions. Setting aside for the moment the fact that many more data points also fall outside the range of what the customer identified as acceptable, the contractor decided to first take steps to ensure the process was behaving in a manner consistent with its known capabilities. Root cause analyses were conducted to discover the external influences causing the statistical outliers (batches 13 and 18). After corrective actions were taken, the process operated in statistical control (that is, no longer exhibiting “out of control” conditions) during the subsequent 22 batches.

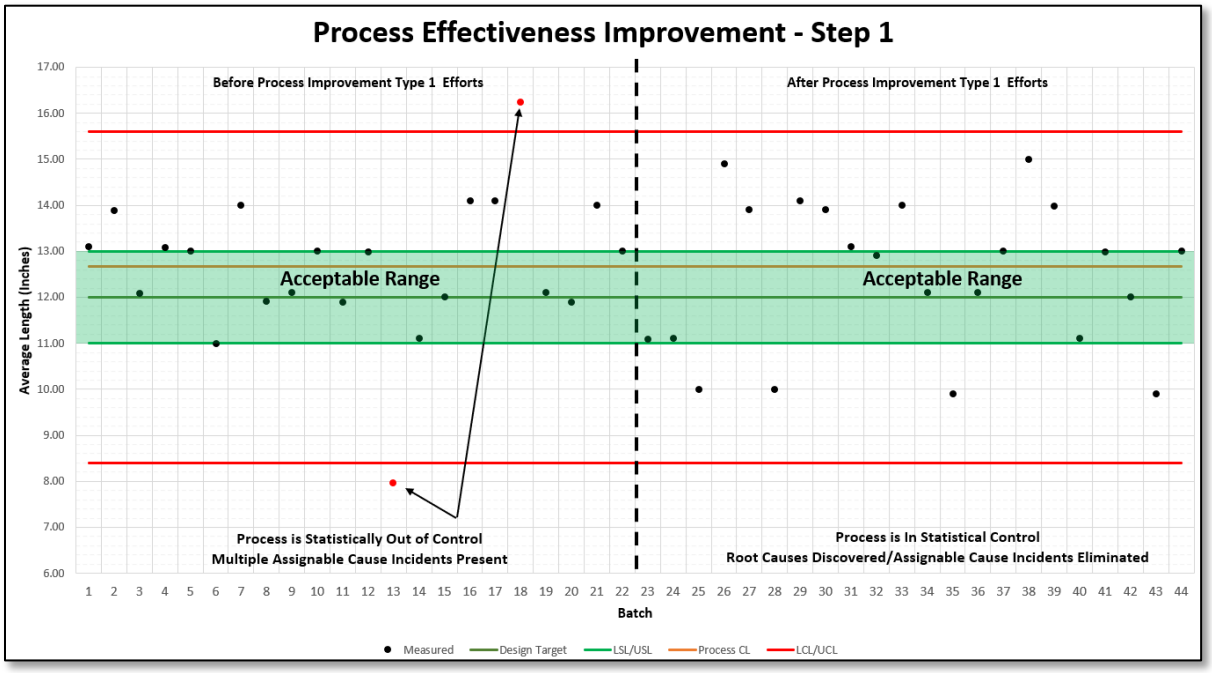

Figure 26: Eliminating assignable causes of process effectiveness variation

When studying the performance of the length cutting process beyond Batch 22, it becomes abundantly clear that “in control” does not mean “good”. Unlike specification limits, control limits are a reflection of reality, not a measure of goodness. To wit, while specification limits impose restrictions on *product* features based on a designer’s implementation of customer requirements, control limits simply describe *process* performance realities. Process capability, the important ratio that quantifies the relationship between product specification limits and process control limits, is described in detail in Section 0.

E.2.1.2.2 Process effectiveness improvement step 1: pursue the ideal

Recall that length cutting process results were brought into control during periods 23 through 44, reproduced on the left side of Figure 27. This positive outcome, however, does not imply that the process is operating optimally, only that it is finally operating as expected. Because the process still possesses much available room for improvement, Step 2 proceeds from where Step 1 concluded. Moving forward, process improvement can manifest in two additional ways:

(1) the process mean will shift closer to the ideal length of 12 inches, and (2) process variability, represented by plus or minus three standard deviations from the average batch length, will approach that ideal more consistently. In the example shown in Figure 27, process improvement efforts produced improvements in both ways: average batch length moved nearly a half inch closer to ideal, and the process variability from that ideal dropped from approximately ± 3 inches to approximately ± 2 inches.

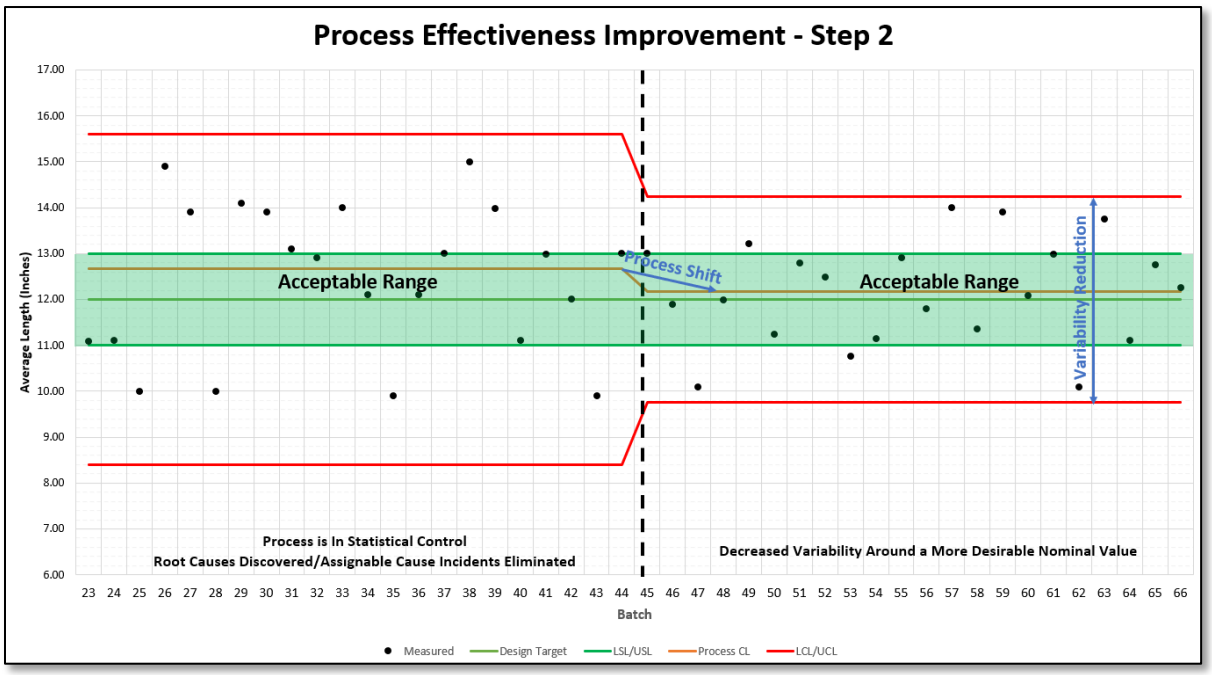

Figure 27: Addressing common causes of process effectiveness variation

Because of its importance in maturing a manufacturing process's effectiveness such that it consistently produces very close to nominal, particularly processes responsible for producing key and critical characteristics, process variability reduction is given special attention in Section 0.

E.2.1.3 Continuous process improvement

Prior to pursuing continuous process efficiency improvement, processes should be carefully evaluated, lest we embark on a journey of improving the efficiency of non-value-added tasks, or a task whose improved individual output does not contribute to improved overall system output (that is, suboptimization). One method of evaluating a system for legitimate process efficiency improvement opportunities is called Business Process Reengineering (BPR). Michael Hammer and James Champy, who elaborate on this aggressive process improvement concept in their bestselling book Reengineering the Corporation, assert: "*American managers must throw out their old notions about how businesses should be organized and run. They must abandon their organizational and operational principles and procedures they are now using and create entirely new ones.*[35]" James Womack and Daniel Jones pursued this objective when they laid out

[35] Hammer, M. and Champy, J. (1993). Reengineering the Corporation, A Manifesto for Business Revolution. HarperCollins Publishers, Inc., p.1.

entirely new operational principles and procedures for American manufacturing organizations, based on the Toyota Production System, in their how-to guide titled Lean Thinking[36]. Lean production concepts skillfully combine both radical process efficiency improvement ("kaikaku") and continuous process efficiency improvement ("kaizen") into a single concept, in five steps:

1. Precisely specify value from a customer perspective.
2. Identify and prune the process value stream to exclude steps failing to add customer value
3. Make the value flow without interruptions
4. Allow the customer to pull value from the production system
5. Pursue perfection through continuous, incremental improvement

Notice the first four steps to becoming lean involve taking drastic steps to fundamentally change the way the production process is performed (kaikaku/BPR), while the fifth and final step adds continuous improvement, motivated by the pursuit of perfection (kaizen).

E.2.1.3.1 Value Stream Mapping

A Value Stream Map (VSM) is the visualization and analysis tool of choice for those embarking on the path of lean thinking. Figure 28 provides a simplified, notional example of an "As-Is" VSM prior to lean conversion. Note the value-added processing time vs production lead time box in the lower right corner. It is not uncommon for the former to be only a very small fraction of the latter, in this case only 5 hours of value-added work is accomplished over a span of 62 workdays. Notice also how much of that production lead time is consumed by parts and subassemblies waiting in storage, either in a warehouse or as WIP. Henry Ford solved this hidden factory problem by eliminating WIP using a moving production line and a variety-limiting policy famously expressed as "*any customer can have a car painted any colour that he wants so long as it is black*"[37]. Since Taiichi Ohno wished to (believed he had to) respond to demand rather than control it, he mimicked the solution by pulling parts and subassemblies through production operations based on customer orders rather than pushing them based on forecasts. Ultimately, the VSM is studied to ensure every process step adds value.

[36] Womack, J. and Jones, D. (1996). Lean Thinking. Simon & Schuster.

[37] Ford, Henry. (1922). My Life and Work. Doubleday, Page & Company. New York. p. 72.

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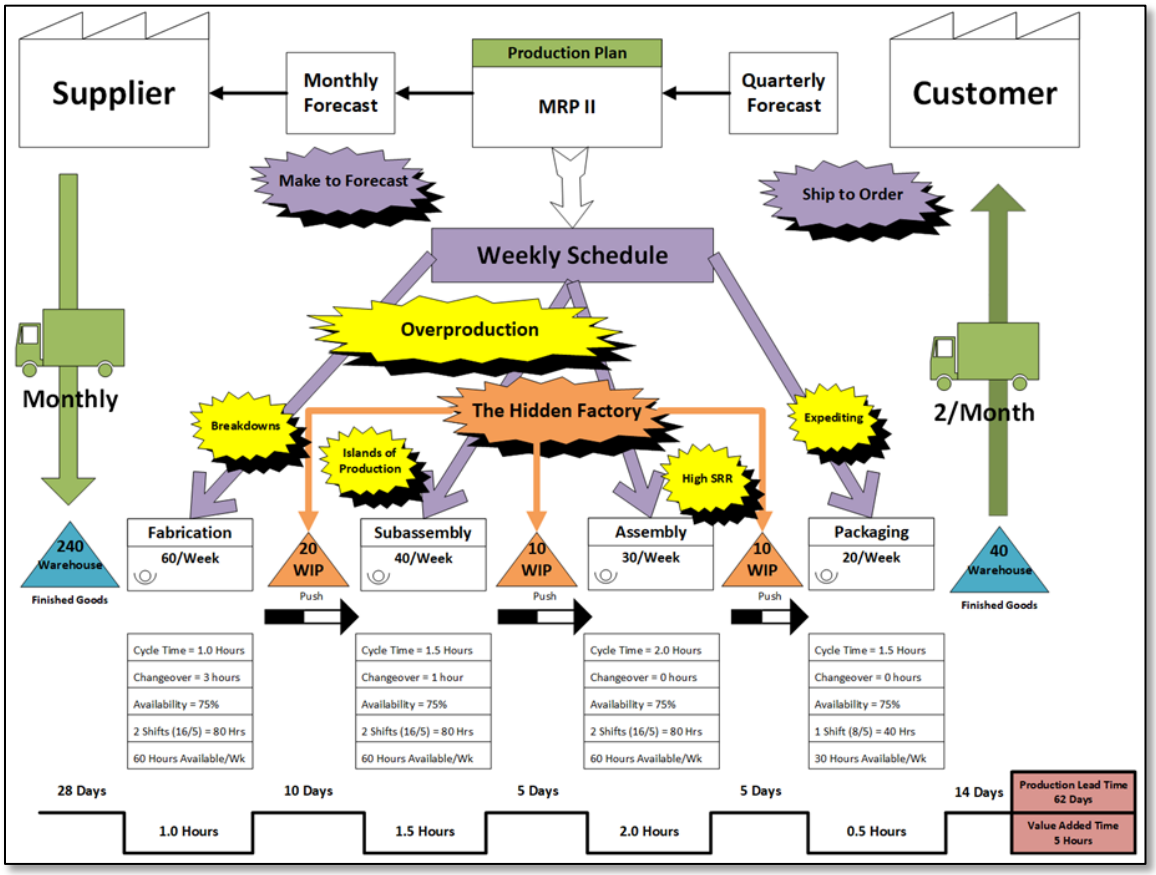

Figure 28: Notional "As-Is" VSM

E.2.1.3.2 VSM as a continuous improvement tool, illustrated

The VSM in Figure 28 hints at one of the causes of WIP: overproduction. While pull-based production scheduling and control systems will mitigate the overproduction problem, pull-based systems are not always practical/desirable. It is extremely important, then, for any push-based production scheduling system being used to recognize that a system of processes is only as capable as its least capable process[38]. Nevertheless, traditional performance measurement and incentive programs have been based on the narrow view of efficiency from a workstation, rather than system, perspective. The "As-Is" VSM appears to be closely tied to this traditional management construct. The following scenario will illustrate how and why production control systems that maximize local efficiencies tend to fail, and then demonstrate that true continuous efficiency improvement elevates the importance of maintaining a total system view of production operations. Consider for now only the capacity limitations shown in the As-Is VSM. An analysis of the system performance, and the contributions of each of the system process steps, is provided in Figure 29.

[38] For a novel-length defense of this assertion, refer to The Goal, by Eliyahu M. Goldratt. Goldratt's fictional character named Jonah, the Socratic character spends the entirety of the story convincing plant manager Alex Rogo that his primary purpose is to make more money for the company, that pursuing increased individual process efficiencies is the wrong way to go about it, and that maximizing productivity of the constraining resource such that system throughput is positively impacted is the right way.

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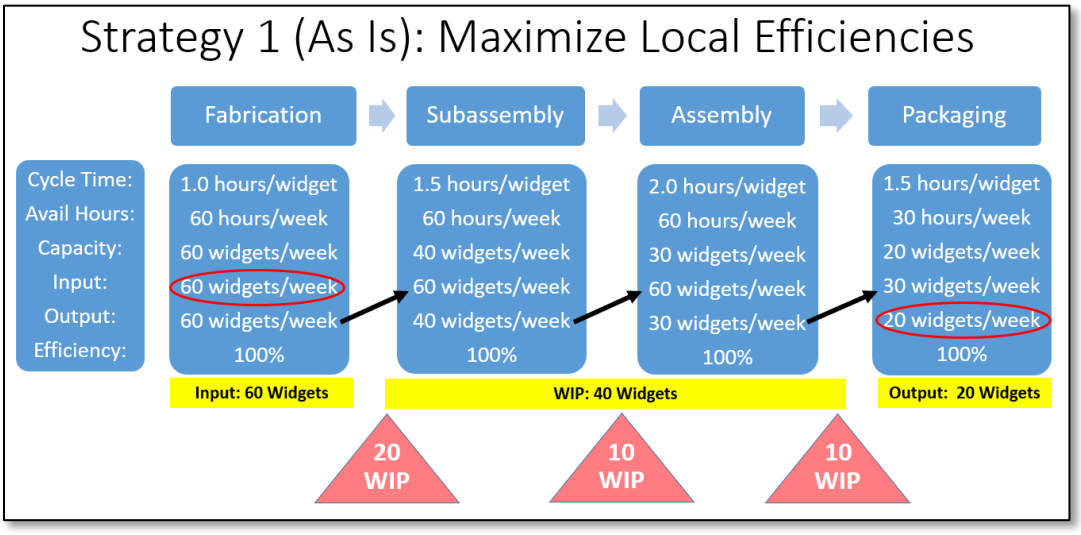

Figure 29: VSM current state: push-based scheduling triggers overproduction/excess WIP

Notice all four process steps are reporting 100% efficiency, yet the system is only completing 20 of the 60 widgets introduced into the system every week. The remaining 40 widgets are scattered throughout the facility in various stages of completeness, waiting for the next operation to be available to process them. Packaging simply cannot keep up with the work the Assembly operation is pushing its way. Assembly cannot keep up with the work Subassembly is pushing its way. Subassembly cannot keep up with the work Fabrication is pushing its way. And fabrication has no intention of slowing down since it is anathema to management when expensive machinery sits idle. As a result, capital consuming WIP accumulates everywhere, and even more capital is being expended on additional temporary storage units to hold it. Hope is not lost. An enterprising young M&Q SME, who has just finished reading The Goal, performs the analysis provided as Figure 30.

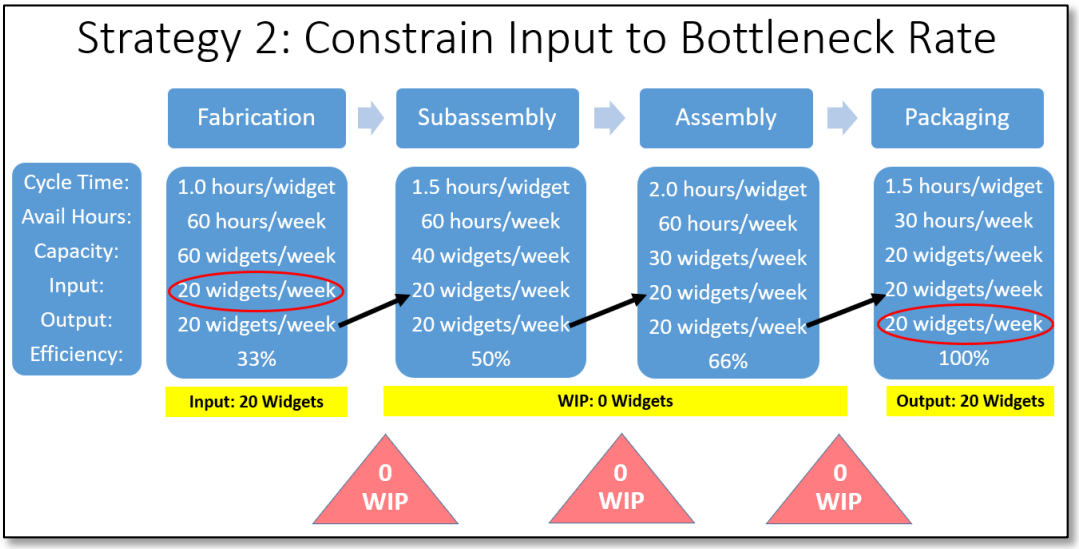

Figure 30: VSM production after limiting production to pacing operation

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The Plant Manager was initially alarmed at the M&Q SME's analysis, and the Fabrication Shop Supervisor, who feared her bonus would be cut if the fabrication shop efficiency dropped so precipitously, also remained skeptical. The Plant Manager came around when the M&Q SME explained that the reduction of WIP meant the temporary storage container orders could be cancelled. The Fabrication Shop supervisor came around when the M&Q SME produced the next part of his analysis shown in Figure 31. This analysis produced recommendations that, if implemented successfully, would increase capacity at the output-constraining Subassembly, Assembly, and Packaging operations to match the output of the Fabrication Shop.

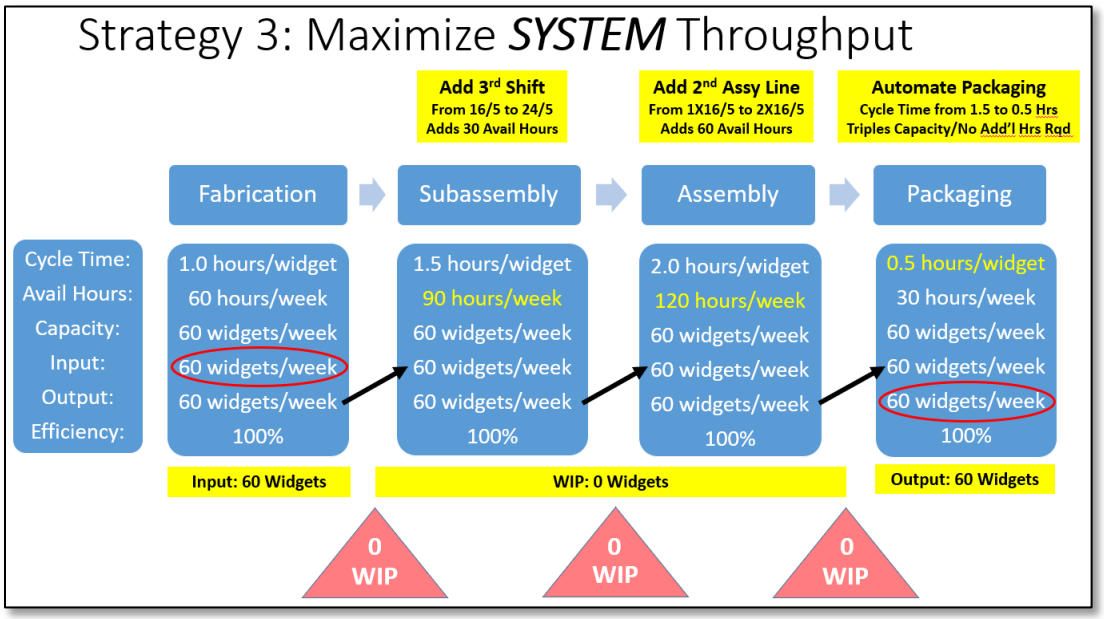

Figure 31: Possible VSM future state

After making the changes indicated in Figure 31, the VSM was updated showing local processes have been optimized, system throughput has been maximized, and non-value-added WIP stores (the hidden factory) have been eliminated (Figure 32).

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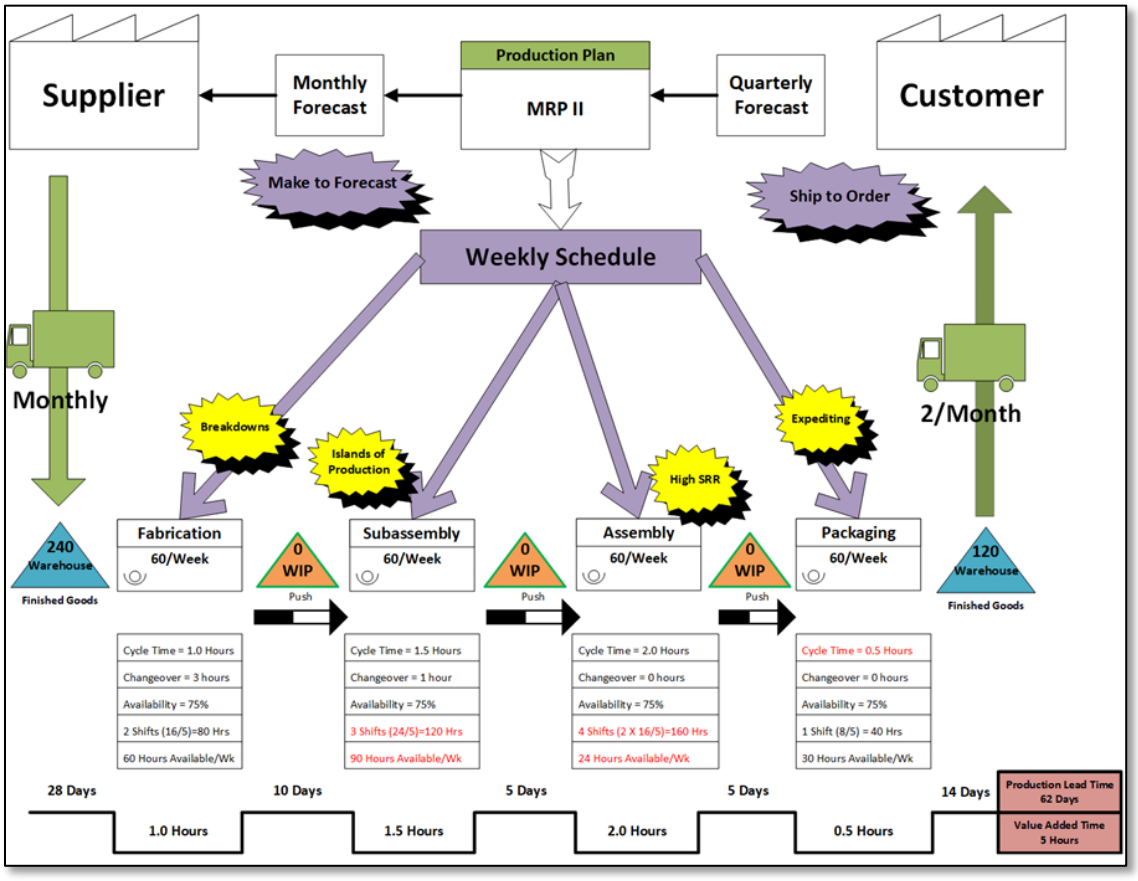

Figure 32: Notional VSM with throughput maximized

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Notice even after the recommended process improvements were implemented, issues, or better stated, opportunities for continued efficiency improvement, remain. Because of the stated frequency of deliveries and shipments, raw materials and finished goods are both accumulating in the warehouse. Those pursuing truly lean operations would likely attack this muda next, perhaps by implementing a scheduling scheme that perfectly synchronizes the rate and timing of supplier shipments, part/subassembly production, and finished goods shipments with customer demand. Doing so, using a customer order triggered scheduling approach (that is, takt) and pull-based production control methods (that is, kanban) yields the VSM shown in Figure 33.

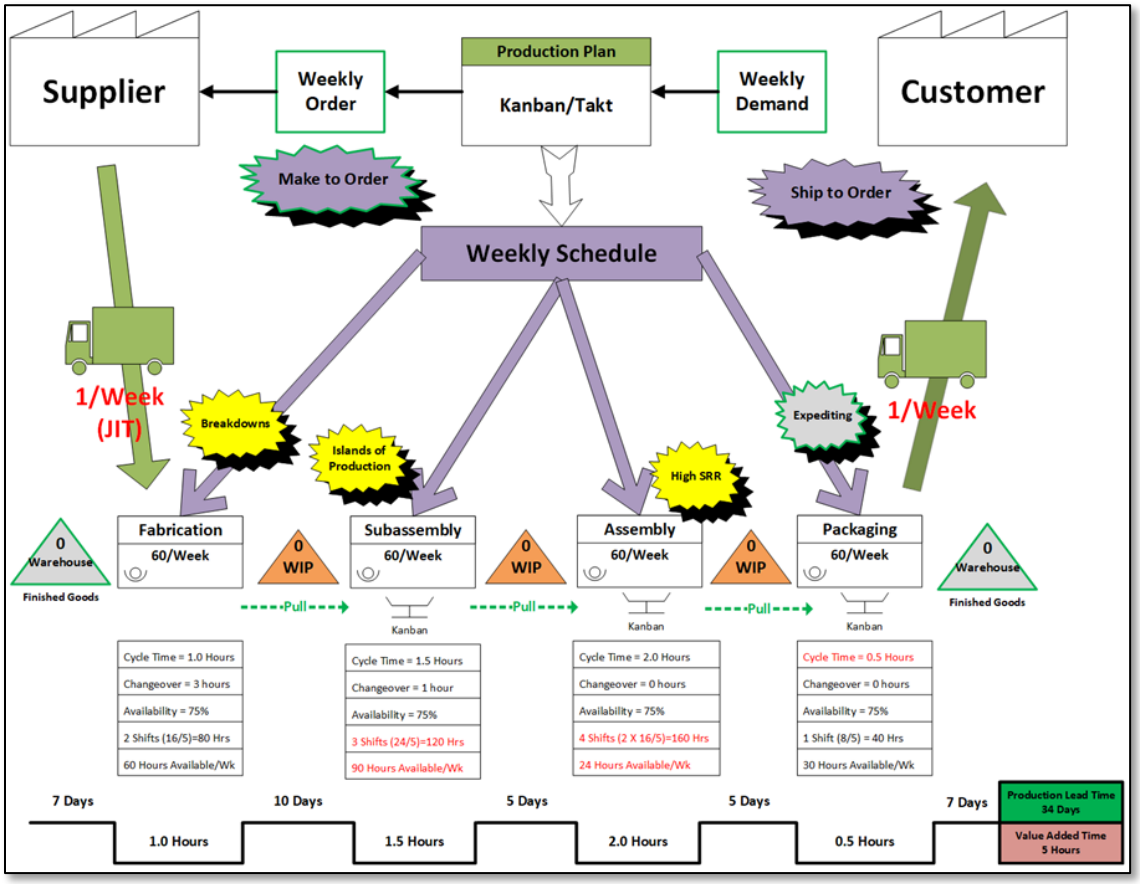

Figure 33: Notional VSM with pull-based scheduling and control

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Order-based scheduling permits just-in-time deliveries of raw materials directly to the Fabrication Shop where kanban signals pull parts and subassemblies through production, culminating in perfectly timed, more frequent shipments matching customer desired delivery dates. Notice this change in operations eliminates the need for both expediting and warehousing (represented by both activities being grayed out). Once these improvements have been deployed, focused continuous improvement efforts may be meaningfully pursued, such as:

1. Implement TPM in the fabrication shop to reduce the occurrence of breakdowns.
2. Implement cellular manufacturing concepts within the fabrication and subassembly to address islands of production; organize work centers around products with similar processing routes (using group technology (GT)) rather than by machine type, possibly enabling takt-based process control in upstream processing steps preceding final assembly.
3. Improve/standardize work instructions in the final assembly area to reduce the incidence of SRR.

This simple exercise was carefully designed to illuminate the importance and benefits of eliminating non-value-added steps (storing raw materials, WIP, and finished goods), maximizing output of constraining resources (managing bottlenecks), and matching production schedules to customer demand (takt-based production scheduling, kanban based production control). It further illustrates how the successful implementation of one improvement can depend on a prior successful implementation of others. Continuous manufacturing process improvement then is, definitionally and philosophically, whether addressing measures of efficiency or effectiveness, the carefully organized persistent pursuit of zero deviation from the ideal.

CONCLUDING MATERIAL

Custodians:

Army – AV

Navy – AS

Air Force – 11

Preparing activity:

Air Force – 11

(Project SESS-2021-023)

Reviewers:

Army – CR

Navy – SA

The activities listed above were interested in this document as of the date of this document. Since organizations and responsibilities can change, you should verify the currency of the information above using the ASSIST Online database at https://assist.dla.mil.