DoD Producibility and Manufacturability Engineering Guide

May 2024

Office of the Executive Director for
Systems Engineering and Architecture

Office of the Under Secretary of Defense
for Research and Engineering

Washington, D.C.

The appearance of external hyperlinks does not constitute endorsement by the United States Department of Defense (DoD) of the linked websites, or the information, products, or services contained therein. The DoD does not exercise any editorial, security, or other control over the information you may find at these locations.

DoD Producibility and Manufacturability Engineering Guide

Office of the Executive Director for Systems Engineering and Architecture
Office of the Under Secretary of Defense for Research and Engineering
3030 Defense Pentagon
Washington, DC 20301
osd-sea@mail.mil | Attn: Specialty Engineering
https://www.cto.mil/sea/

DOPSR Case # 24-T-1876

Approved by
Principal Deputy Executive Director for Systems Engineering and Architecture
Office of the Under Secretary of Defense for Research and Engineering
May 2024

DoD Producibility and Manufacturability Engineering Guide Change Record

Date	Change	Rationale

Contents

Figures

Tables

1 INTRODUCTION

This guide describes the elements of Department of Defense (DoD) producibility and manufacturability engineering over the system life cycle. This guide will be updated periodically to reflect current policy, guidance, tools, and best practices. This document does not supersede DoD policy, regulation, or law.

This guide includes a compilation of best practices for conducting producibility and manufacturability activities across the DoD system acquisition life cycle. In short, both producibility and manufacturability promote ease of manufacture of defense systems. Producibility focuses on design considerations while manufacturability focuses on improving manufacturing processes and factory floor operations.

This guide is intended primarily to assist manufacturing and quality (M&Q) engineers to provide input to systems engineering activities starting with initial system concept and product design and continuing throughout the life cycle. The guide provides useful definitions, references, tools, and best practices. Although written primarily for M&Q practitioners, the guide includes information for engineering and technical management (ETM) and acquisition functional disciplines including design engineering, program management, contracting, logistics, and procurement.

DoD Instruction (DoDI) 5000.88, Engineering of Defense Systems, 3.6.c, refers to manufacturing and producibility as follows (emphasis added):

> The production, quality, and manufacturing (PQM) lead,[1] working for the Program Manager (PM), will ensure **manufacturing, producibility, and quality risks are identified and managed throughout the program's life cycle.**
>
> (1) Beginning in the materiel solution analysis phase, **manufacturing readiness and risk will be assessed and documented in the Systems Engineering Plan (SEP).**
>
> (2) By the end of the Technology Maturation and Risk Reduction (TMRR) Phase, **manufacturing and quality processes will be assessed and demonstrated** to the extent needed to verify that risk has been reduced to an acceptable level.
>
> (3) During the Engineering and Manufacturing Development (EMD) Phase, **the PQM lead will advise the PM on the maturity of critical**

[1] 10 USC 1706 (12) requires Major Defense Acquisition Programs to have a program lead for production, quality, and manufacturing (PQM). As of October 2021, the PQM function is included in the DoD Acquisition Workforce Engineering and Technical Management (ETM) functional career field. According to DoDI 5000.66, "Defense Acquisition Workforce Education, Training, Experience, and Career Development Program," the ETM Functional Area Lead determines specific requirements for PQM Key Leadership Positions.

manufacturing and quality processes to ensure they are affordable and executable.

(4) Before a production decision, the PQM lead, working for the PM, will ensure that:

(a) **Manufacturing, producibility, and quality risks are acceptable.**

(b) **Supplier qualifications** are completed.

(c) Any applicable **manufacturing processes are or will be under statistical process control (SPC).**

The manufacturing and quality leads should act as advocates to allow the system development, acquisition, and sustainment project teams to become familiar with the major producibility and manufacturability concepts and activities. In Figure 1-1, producibility-focused activities in the design process are highlighted in light blue, and manufacturability activities focused on optimizing manufacturing operations are highlighted in dark blue. Each of these major activities will be discussed in later sections of this guide.

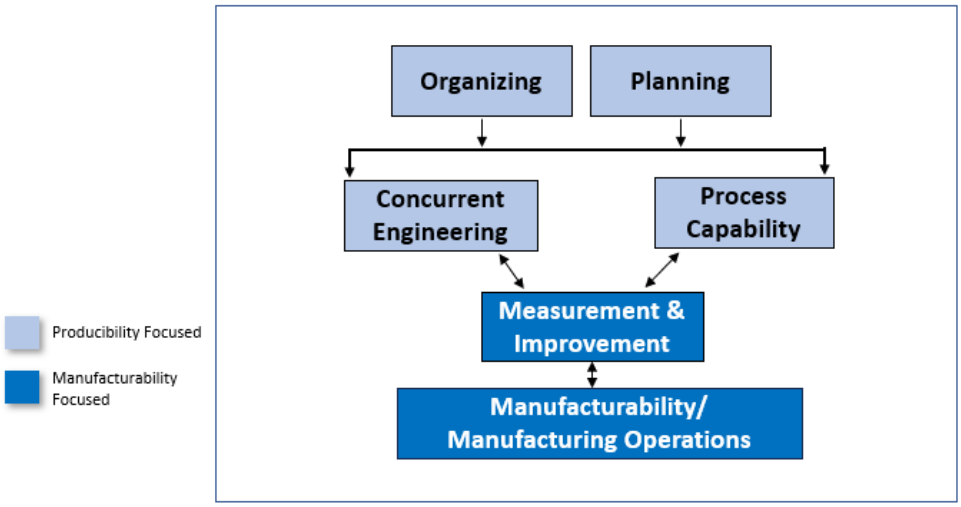


Figure 1-1. Major Ease-of-Manufacture Activities

1.1 Background

Senior DoD M&Q leadership identified the need for updated producibility and manufacturability guidance. Most available DoD guidance was published during the 1980s and 1990s and needed to be updated with current DoD engineering practices and advanced manufacturing capabilities. At the same time, many of the producibility and manufacturability practices contained in previous guidance and standards remain constant and should be emphasized as key considerations for system development teams.

In addition to enduring producibility and manufacturability principles and practices, this guide addresses current systems engineering guidance and advanced manufacturing capabilities such as digital engineering, Industry 4.0 applications, Lean/Six Sigma, and technical data to enhance the ease of manufacture.

1.2 Guide Overview

The guide will:

- Describe guidance for DoD M&Q engineers and design teams to attain producible systems, assemblies, components, and parts.
- Provide an overview of the principles of producibility and how they are applied to design efficiently manufactured products that meet performance requirements to avoid schedule delays or rework.
- Discuss producibility considerations during development and design phases starting with early system concept development through detailed design.
- Outline the role of producibility during Systems Engineering Technical Reviews (SETRs) and technical audits.
- Describe manufacturability efforts during manufacturing operations and sustainment to improve ease of manufacture.
- Address advanced manufacturing (Industry 4.0) technologies and digital engineering to enhance producibility and manufacturability.
- Provide an overview of the relationships among producibility, manufacturability, quality, and reliability.
- Describe key definitions, descriptions of terms, concepts, references, and analytical tools.
- Discuss example contracting considerations to include producibility and manufacturability requirements in DoD source selections, requests for proposals, and contracts.
- Provide sample Producibility Plan approaches and description of expected plan content.

Following this introduction, Sections 2 and 3 provide an overview of producibility and manufacturability concepts, terms, and principles.

Section 4 focuses on organizing for producibility. As part of the design Integrated Product Team (IPT), M&Q practitioners should proactively take a leadership role and advocate for producibility considerations during system design. This section also introduces the concept of concurrent engineering focusing on development of both the product and manufacturing processes as the system design progresses.

Sections 5 through 7 describe major producibility activities including producibility planning, concurrent producibility engineering, and process capability and control. This discussion addresses producibility as a design consideration starting with system concept development and

detailed product design. Producibility should be addressed as part of SETRs and audits and by integration of producibility into systems engineering practices.

Section 8 provides an overview of manufacturability and improving the ease of manufacture during manufacturing operations. This includes major concepts such as:

- Continuous process improvement.
- Measuring process capability and control.
- Statistical process control.
- Lean manufacturing (section 8 provides additional detail).

Section 9 provides a description of advanced manufacturing and potential applications of digital engineering, modeling and simulation, digital manufacturing, and Industry 4.0 technologies to enhance producibility and manufacturability.

Section 10 introduces best practices for including producibility and manufacturability requirements in DoD contracts with suggested manufacturing input to the Request for Proposal (RFP), further outlined in Appendix D.

Additional appendices include a summary of common producibility and manufacturability tools (Appendix A), example producibility analysis worksheets (Appendix B), reproducibility and repeatability assessment techniques (Appendix C), and a sample producibility plan outline (Appendix E).

Where applicable, a list of key references directly related to the topic are included following a topic discussion. A complete list of references and sources is included at the end of the document.

Producibility and manufacturing engineering principles, tools, and techniques apply to all DoD acquisition pathways that require production or manufacturing of a product. Sections of this guide present examples (e.g., SETRs) that apply specifically to the Major Capability Acquisition (MCA) pathway as outlined in DoDI 5000.85, Major Capability Acquisition. Producibility and manufacturability efforts should be tailored for other Adaptive Acquisition Framework pathways and program-unique requirements. In addition, producibility and manufacturability concepts are not limited to mission systems and subsystems. This guide applies to any “product” to be manufactured throughout the life cycle such as weapon systems, business systems, maintenance trainers, simulators, and peculiar support equipment etc., and applies to manufacturing throughout the system life cycle.

2 OVERVIEW OF PRODUCIBILITY AND MANUFACTURABILITY

Producibility and manufacturability are intended to enhance the relative ease of producing a product (ease of manufacture). Other desired outcomes embedded in ease of manufacture concepts are consistent, repeatable processes, and products that meet requirements for performance, quality, reliability, and maintainability. Producibility and manufacturability both play a role in ease of manufacture and are interrelated, and they have the same objective across the system life cycle.

The terms "producibility" and "manufacturability" are often used interchangeably. This guide distinguishes between producibility and manufacturability as distinct but complementary concepts. For example, the DoD Systems Engineering Guidebook and Manufacturing Management Program Guide (MIL-HDBK-896) define producibility as a design accomplishment. Some well-known concepts such as "Design for Manufacture (DFM)," "Design for Manufacturability," or "Design for Manufacture and Assembly (DFMA)" refer to manufacturability—but are focused on product and process design. This guide discusses DFM and DFMA as approaches to achieve a producible design. It then discusses manufacturability as approaches focused on ease of manufacture to improve manufacturing operations. Manufacturability focuses more on optimization of factory floor efficiency to enhance ease of manufacture during manufacturing operations.

Producibility is a *design* consideration to facilitate ease of manufacture, that is, designing a product in a way so it is easy to manufacture. Development teams should consider producibility during system development and design following detailed design guidelines and producibility principles.

Manufacturability addresses *manufacturing operations* to enhance the ease of manufacture by developing and implementing efficient manufacturing processes. Examples include advanced quality planning, Lean manufacturing, Process Failure Modes and Effects Analysis, and continuous process improvement.

As producibility and manufacturability have a common objective of enhancing the ease of manufacture, several interrelated and interdependent elements and engineering activities affect both product design and manufacturing operations. Producible designs can be manufactured more easily, while improvements in manufacturability give designers more trade options that can enhance producibility. To improve the ease of manufacture, each process provides feedback to the other as illustrated in Figure 2-1.

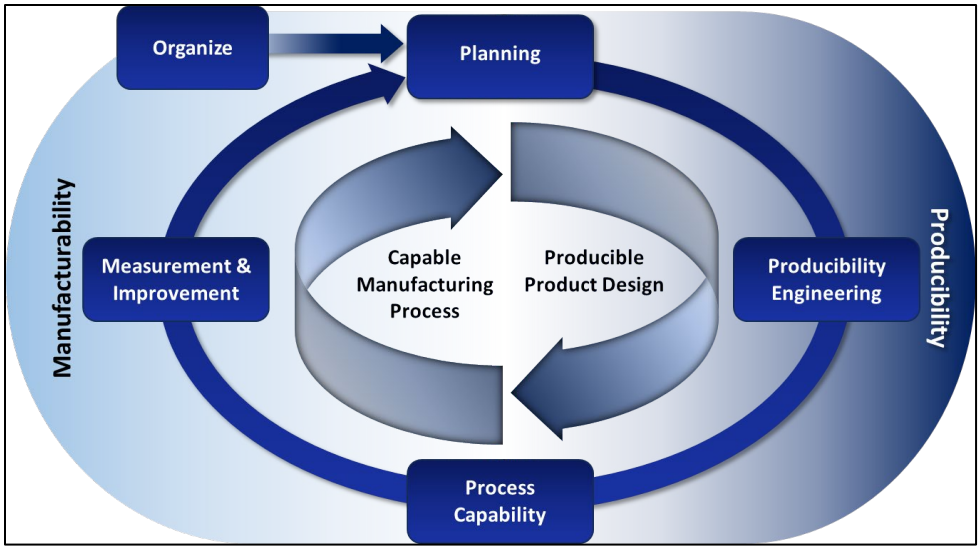


Figure 2-1. Feedback between Producibility and Manufacturability

Understanding what contributes to ease of manufacture can assist program personnel to identify methods to improve producibility and manufacturability. A positive change to one or more of the elements of manufacturing depicted in Figure 2-2 will most likely enhance ease of manufacture and reduce life cycle cost.

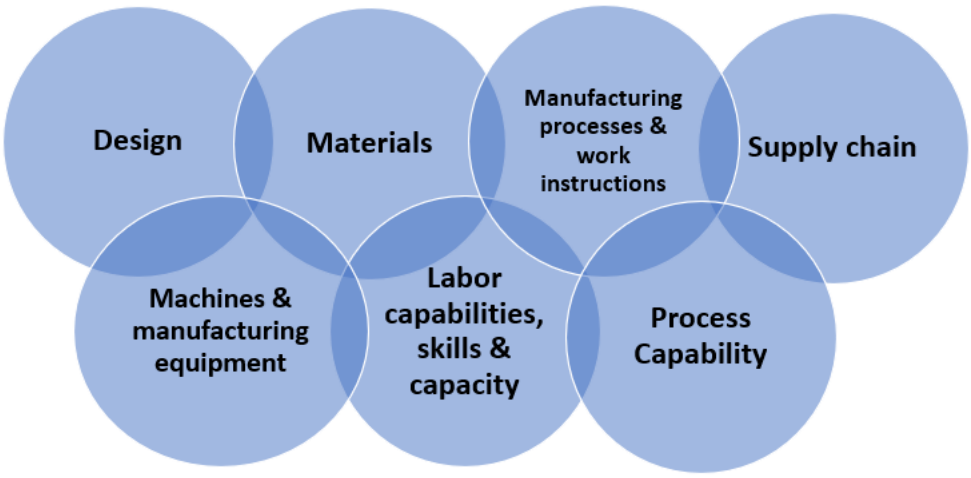


Figure 2-2. Major Elements Influencing Ease of Manufacture

DoD uses the terminology of "producibility" throughout its engineering policy and guidance documents, such as:

- DoDI 5000.88, Engineering of Defense Systems.
- Systems Engineering Guidebook.

- Engineering of Defense Systems Guidebook.
- DoD Systems Engineering Plan (SEP) Outline.
- DoD M&Q Body of Knowledge.
- DoD Early M&Q Engineering Guide.
- MIL-HDBK-896, Manufacturing Management Program Guide.
- DoD Manufacturing Readiness Level assessment criteria (e.g., Producibility sub-thread).

Producibility terms are also used in Defense Acquisition University (DAU) training materials and the SAE AS6500A, Manufacturing Management Program (non-government standard).

Academia, literature, and commercial industry often use the term “manufacturability” versus “producibility.” Example terms include “design for manufacturability,” “design for manufacturability and assembly,” or “design for manufacture.”

This guide outlines both producibility and manufacturability concepts and activities and provides additional guidance for integration into current DoD engineering policies, tools and techniques, and evolving manufacturing technologies to enhance the ease of manufacture.

3 PRODUCIBILITY CONCEPTS

Producibility is an important design consideration for product teams. The DoD Systems Engineering Guidebook (2022) highlights producibility as follows:

> Producibility is a design accomplishment for the relative ease of manufacturing. Like manufacturing and other system design functions, producibility is integral to delivering capability to the warfighter effectively and efficiently. Producible designs are lower risk, more cost-effective, and repeatable, which enhances product reliability and supportability. (page 173)

Relevant to defining producibility as a design accomplishment DoD military standard, MIL-STD-1528, "Manufacturing Management Program" (rescinded), described producibility as,

> …a design accomplishment that enables manufacturing to repeatably fabricate hardware which satisfies both functional and physical objectives at an optimal cost. Producibility results from a coordinated effort by systems/design engineering and manufacturing/industrial engineering to create functional hardware designs that optimize ease and economy of fabrication, assembly, inspection, test, and acceptance of hardware without sacrificing desired function, performance, or quality. A producible design includes complete design engineering and manufacturing planning consideration for the selection of material, tooling, facilities, capital equipment, test equipment, methods, processes, and personnel to be employed in the production of hardware to that design. Production quantities and rates are critical factors affecting producibility and must be taken into account whenever the producibility of design alternatives is assessed. Effective hardware producibility supports reliability and maintainability requirements and is fundamental to life cycle cost objectives. (page 4)

The U.S. Navy "Producibility Systems Guidelines" (NAVSO P-3687) defines producibility as,

> …the relative ease by which a product can be manufactured as measured in yield, cycle times, and the associated costs of options in product designs, manufacturing processes, production and support systems, and tooling. (page 3)

NAVSO P-3687 encourages design teams to assess producibility at both the product and enterprise levels (e.g., system design, organizational processes, prime contractors, and throughout the supply chain). As a best practice, the PM should implement producibility engineering and planning efforts early and should continuously assess the integrated processes and resources needed to achieve producibility. NAVSO P-3687 guidance refers to the integrated process and resources needed to achieve producibility as a "producibility system" composed of five steps:

1. Establish a producibility infrastructure.

2. Determine process capability.
3. Address producibility during conceptual design.
4. Address producibility during detailed design.
5. Measure producibility.

Table 3-1 outlines enduring principles designers use to identify components and detailed designs that can be manufactured at minimal cost and enhance the ease of producing a product.

Table 3-1. Principles of Producibility (Product Design)

Principles
Simplify the design – Based on the "simpler is better" principle, systems with fewer parts have fewer things to go wrong, whether in production (producibility), or in operational performance (reliability). Simpler designs are easier to assemble, less costly and more straightforward regarding procuring materials, have fewer opportunities for interoperability conflicts, and streamline inventory.
Use standard materials and components – There is no reason to use exotic materials when more conventional ones will perform the same function. Standard materials possess more extensive experience bases. Properties are better understood, materials can be purchased at more favorable rates, and new training for the workforce is minimized.
Use standard product design – For similar products, specify the same materials, parts, and subassemblies as much as possible. Standardization provides economy of scale, simplified process control, and reduced training and tooling investment.
Design modular assemblies and subassemblies – Creating modular designs for assemblies allows for the modification of a product while still maintaining its overall design intent/functionality. In doing so, multiple products/modifications can be completed while streamlining the manufacturing process.
Use economical materials – Avoid selecting materials that are more expensive than necessary; however, do not purchase inferior materials at the expense of reliability and performance.
Use liberal tolerances when possible – Higher cost and manufacturing effort are related to extra manufacturing operations such as grinding, honing, greater precision tools, increased machine maintenance, higher scrap, and rework costs, need for increased skill levels, higher material costs, and higher investment in precision equipment.
Define acceptable surface finishes – Surface finishes should be selected for functionality rather than aesthetics.
Design for efficient joining – Identify and analyze potential ways to join parts without the use of fasteners, screws, or adhesives. If any of the methods must be used, attempt to keep the quantity, size, and variation of the fasteners to a minimum while making use of standardized sizes.
Minimize lead times – Use parts and materials from responsive suppliers who can deliver materials and supplies on time without costly delays.
Use acceptable materials – Using certified or industry accepted materials will streamline qualification and testing and will avoid a host of unexpected fabrication and test issues (i.e., use of hazardous or sole source materials). Select DMSMS resilient parts, which are parts with significant time left in the life cycle, and with viable replacement options.
Make it easy to inspect – Higher inspectability is a key to meeting schedule and test goals. Lower inspectability causes schedule delays and added costs.

Source: Derived from Bralla (1986) and DAU PQM 301 course materials.

Table 3-2 outlines principles of process design.

Table 3-2. Principles of Producibility (Process Design)

Principles
Reduce touch labor – Reduce the number of times that workers and machines touch the product.
Minimize steps – Eliminate or reduce process steps. Minimize adjustments and re-orientation during fabrication and assembly. Locate and identify tooling and parts inventory for efficient access to reduce worker movement.
Design factory for ergonomics – Design workspaces and tooling for unobscured access and vision; and ease of handling of parts and tools (e.g., waist height vs. overhead). Design workspaces that would minimize repetitive motion injury (e.g., carpel tunnel, tennis elbow, tendinitis)
Error proof processes – Single direction assembly; only one way to assemble. Document and update clear and current work instruction.
Understand process capability – Develop quantitative measures of process capability (Cp) and process capability index (Cpk) and maintain process control.
Use repeatable processes – Select fabrication processes that are repeatable and reproducible. Repeatable processes reduce defect and rework rate and simplify manufacturing for the workforce.
Minimize skill levels – To the degree possible, use manufacturing processes that require less skill. Minimizing skill level reduces the training time for the workforce and makes it easier to hire adequately skilled workers.
Minimize energy consumption – To the degree possible, use less energy-intensive processes, which will help contain costs.
Minimize special test equipment – Avoid specifying specialized testing equipment and procedures. These will result in added test and evaluation costs, as well as schedule delays at reviews. Confidence in data from specialized tests is typically not as high as data from standard tests.
Use economical manufacturing techniques – To the degree possible, avoid fabrication processes that are more costly than necessary.
Minimize scrap and waste – Minimize the use of highly subtractive material removal processes. Minimizing scrap cuts down foreign object damage, recycling costs, and processing time, among other benefits.
Design for expected level of production – Consider economic quantity such as minimizing labor-intensive processes or complex tooling for high volume components.

Source: Derived from Bralla (1986) and DAU PQM 301 course materials.

In addition, cross-cutting producibility and manufacturability concepts include process capability and variability reduction:

- *Process capability:* A statistical measure of the inherent process variability of a given characteristic. As a best practice, process capability assessment should be conducted throughout the entire life cycle, to include developing projected process capability assessments, determining required process capabilities, producibility planning, and assessments to measure and improve manufacturing capabilities during production.

- *Variability reduction:* A systematic approach to reducing product and process variability to reduce unwanted condition or difference (variation) between a current and desired end state. Variability reduction seeks to find the root causes of variation and reduce or eliminate the source. Reducing variation will likely improve ease of manufacture while also improving product performance, reliability, and quality.

4 ORGANIZE FOR PRODUCIBILITY

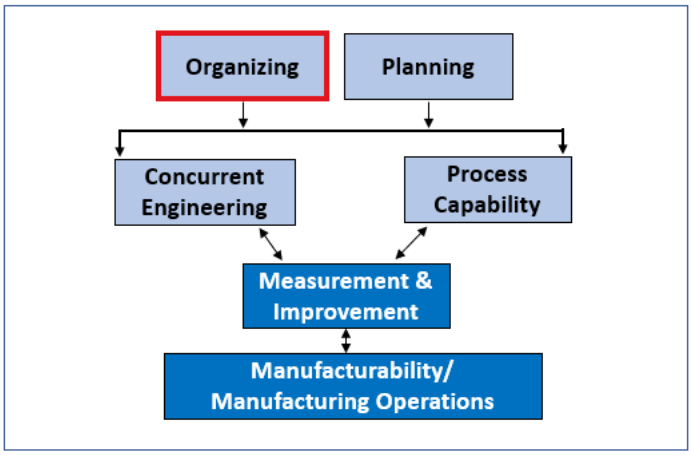


Figure 4-1. Major Producibility Activities: Organize for Producibility

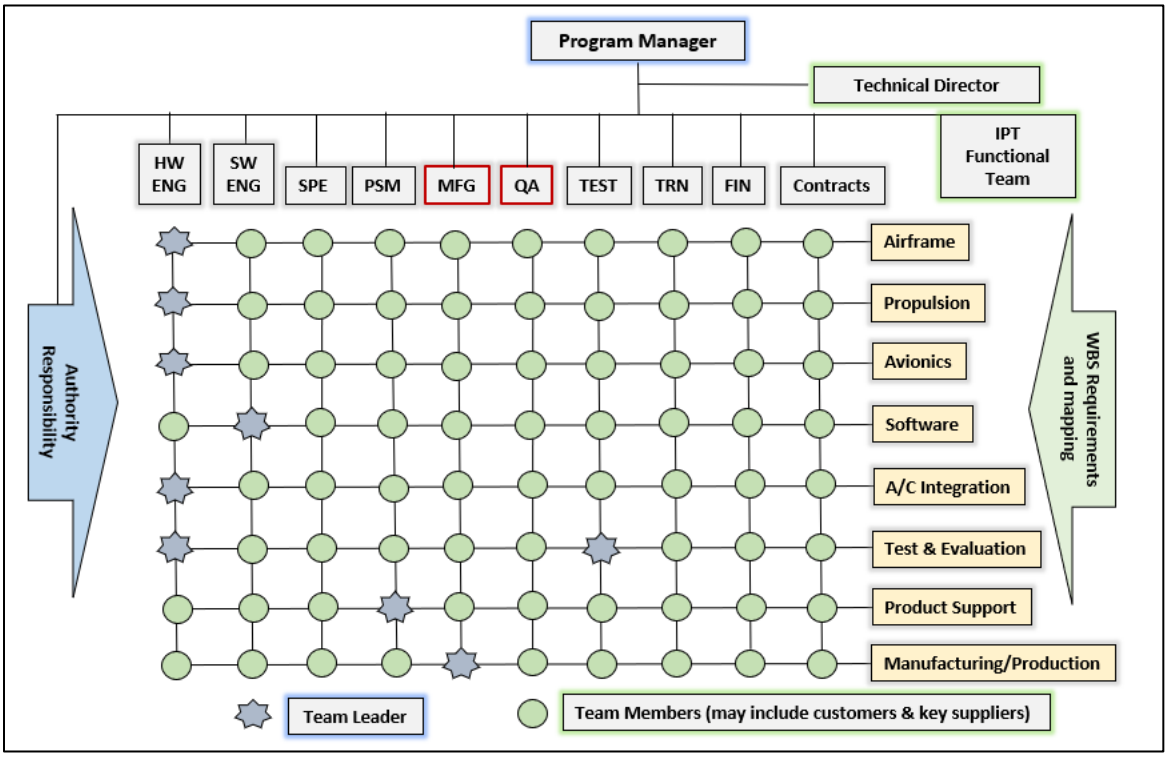
Project leaders should organize teams to foster producibility, a design consideration that results from a coordinated effort by engineering specialties. This activity is highlighted in red (bold outline) in Figure 4-1 and will be discussed in this section. The design team may include functional specialists such as design engineers (e.g., electrical, mechanical, aerospace, materials, thermodynamics) and specialists in reliability and maintainability (R&M), system safety, human systems integration, manufacturing, quality, test, software, configuration management, and logistics. Involvement and communication start at the earliest stages of development as the product design progresses.

The IPT is composed of representatives from appropriate multifunctional disciplines working together to build successful programs, identify and resolve issues, and make sound and timely recommendations to facilitate decision making. IPTs are necessary for organizing for producibility and for implementing producibility and manufacturability throughout the life cycle of a product or weapon system.

The objective of organizing for producibility and manufacturability is to create a functional design that optimizes the ease and economy of fabrication, assembly, inspection, test, and maintenance, without sacrificing desired function, performance, or quality. This coordinated effort often is referred to as concurrent engineering and is accomplished by IPTs.

As a best practice, the IPT responsible for the product development should include M&Q subject matter experts to address producibility considerations throughout the entire design process. These M&Q specialists on the IPT may have titles such as: manufacturing engineer, industrial engineer, process engineer, quality engineer, Lean manufacturing specialist, manufacturing team lead or manager, and tooling specialist, etc. Including M&Q personnel in the program team organization will most likely enhance concurrent engineering during detailed design. Figure 4-2

depicts a notional IPT structure with manufacturing and quality assurance practitioners highlighted in red ("MFG" and "QA").



Source: Derived from DAU course materials.

Figure 4-2. Notional IPT Structure

In accordance with DoDI 5000.88 and the DoD SEP Outline, the program SEP must include the program office IPT structure indicating team members, roles and responsibilities, authorities, products, and metrics, unless waived by the SEP approval authority. M&Q IPT members should provide input to ensure that producibility activities are documented as part of the program's technical management organization and activities. In addition, the contractor's IPT information, including manufacturing and producibility, should be documented in the Systems Engineering Management Plan (SEMP).

Integrated Product and Process Development (IPPD): IPPD emphasizes the importance of developing both the product and processes concurrently, and these activities should be accomplished by a multidisciplinary team. The project team organization, to include M&Q specialists, should develop the product and processes simultaneously as the design progresses. IPPD is a management technique that expands upon concurrent engineering by simultaneously integrating all essential acquisition activities through IPTs to optimize design, manufacturing, producibility, and supportability processes. IPPD and concurrent engineering facilitate meeting cost and performance objectives from product concept through production, including field support.

IPPD tenets include:

- **Program and Engineering Management Commitment:** Integrate producibility and process development into design of the product, which requires management support.
- **Customer Focus:** Satisfy customer needs better, faster, and at less cost by including the customer in decision making and on all multidisciplinary teams.
- **Concurrent Development of Products and Processes:** Develop processes concurrently with the products they support.
- **Early and Continuous Life Cycle Planning:** Begin planning for a product and process early and extend the planning throughout the product's life cycle. Early life cycle planning, which includes customers, functions, and suppliers, should provide a solid foundation for the various phases of a product and its processes.
- **Flexibility for Optimization and Use of Contractor Approaches:** Provide maximum flexibility to optimize use of effective contractor processes and commercial specifications, standards, and practices.
- **Robust Design and Improved Process Capability:** Encourage use of advanced design and manufacturing techniques that (1) promote achieving quality through design and products with little sensitivity to variations in the manufacturing process (robust designs); and (2) focus on process capability and continuous process improvement. Use tools such as Six Sigma process control and Lean manufacturing concepts.
- **Event-Driven Scheduling:** Relate program events to their associated accomplishments and accomplishment criteria.
- **Multidisciplinary Teamwork and Empowerment:** When making decisions, consider diverse perspectives (e.g., engineering, manufacturing, test, logistics, financial management, contracting personnel), including customers and suppliers.
- **Proactive Identification and Management of Risk:** Identify risks, issues, and opportunities (RIO) relevant to cost, schedule, and technical performance requirements, and document the information and mitigation plans in RIO management processes.

5 PLAN FOR PRODUCIBILITY

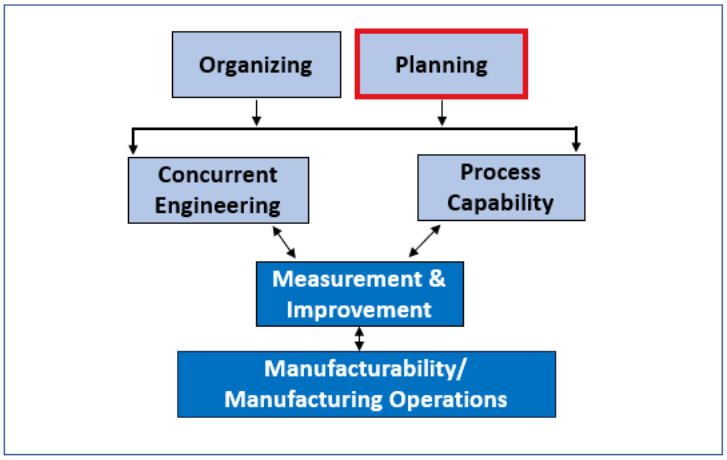


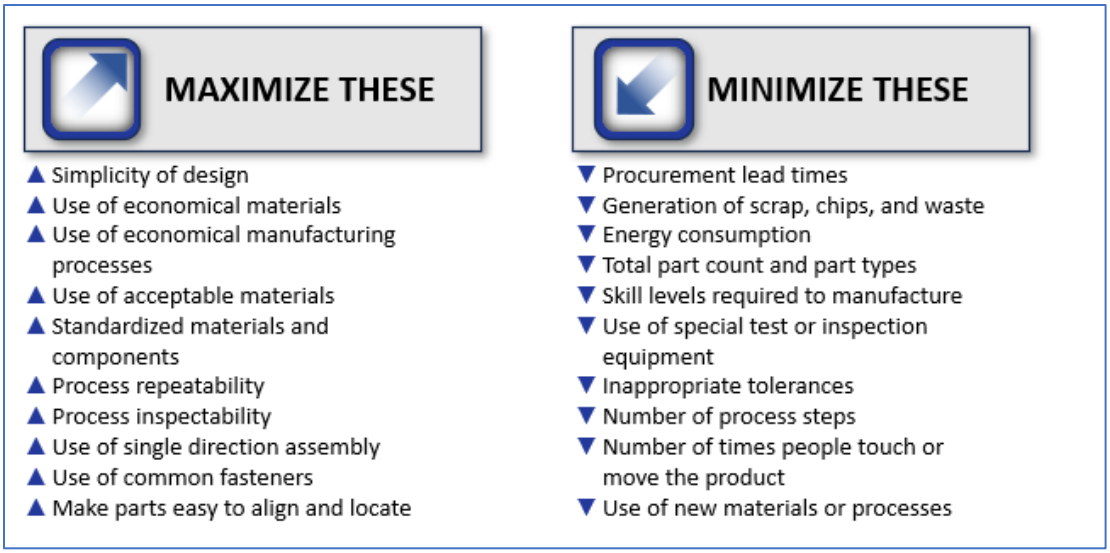
Figure 5-1. Major Producibility Activities—Plan for Producibility

5.1 Overview

Producibility focuses on making a product easier to manufacture. Advance planning activities, indicated in red (bold outline) in Figure 5-1, will be discussed in this section. Planning for producibility is intended to ensure that the design of a part, component, assembly, subsystem, or system is ready for production and optimized to achieve program goals at the least cost. Producibility planning is a continuous process that should begin during the early system concept development and continue through design and manufacturing operations.

A primary objective of producibility planning includes influencing the design itself but also includes the facilities, manpower, machines, materials, and measurement systems used to produce the item at the rates and quantities needed with acceptable quality.

A second major objective of producibility planning is to optimize the production process. This includes having multidisciplinary functional engineers and managers (manufacturing, industrial, quality, reliability, and maintainability, etc.) influence the design so the final design can be produced efficiently using proven production processes and available production capacity. Then during manufacturing operations under continuous process improvement, the team will measure, control, and improve the production processes to improve efficiency, quality, and reduce costs (see Section 8). Producibility planning focuses on the following design and process factors that should be increased (maximized) or reduced (minimized), when possible, as outlined in Figure 5-2.



Source: Derived from DAU course materials.

Figure 5-2. Sample Producibility Objectives

5.2 Support to Early Development Government IPTs

On smaller early development projects when the government project team has limited personnel or the IPT does not include M&Q subject matter experts, the technical team lead should budget for and request M&Q support from independent sources (i.e., Service manufacturing functional leaders, defense agencies, laboratories, Federally Funded Research and Development Centers (FFRDCs), or other government technical resources) to assist in pre-Preliminary Design Review (PDR) manufacturing activities or to conduct independent manufacturing feasibility assessments.

For early development projects focused on fielding major weapon systems such as advanced fighter and bomber aircraft, major land combat systems, ships/submarines, space systems, missile defense, or hypersonic weapons, etc., involving large development teams and resources, program technical leadership should include one or more manufacturing specialists on the early development project technical team and should include these specialists as the system proceeds through initial to detailed design. If suitable resources are not available (as with smaller development teams), the technical team lead should also proactively budget for and request support from independent sources.

5.3 Producibility Input to the Systems Engineering Plan

For the MCA pathway, DoDI 5000.88 requires a SEP for all MDAP programs unless waived by the approval authority. A SEP is also required for all Acquisition Category (ACAT) II and II programs unless waived by the DoD Component. For M&Q, DoD 5000.888 further states, "…Beginning in the Materiel Solution Analysis phase, manufacturing readiness and risk will be assessed and documented in the Systems Engineering Plan (SEP)" (page 22).

The SEP documents the PM's and Lead Systems Engineer's approach to manage the systems engineering (SE) activities and defines the methods for implementing all system requirements having technical content, technical staffing, and technical management. The SEP should include producibility planning and execution as an inherent aspect of "manufacturing readiness." As a best practice, manufacturing engineers should document producibility planning in the SEP starting during Materiel Solution Analysis (MSA) and the Milestone A SEP (see SEP Outline).

The M&Q lead should provide input to the IPT to describe the approach for implementing and contracting for comprehensive manufacturing and quality programs to include producibility, integrating producibility with SE processes, and timing for key producibility activities. Table 5-1 illustrates the mandatory SEP planning summary (SEP Outline, Table 3.2-5) to include reporting on Industrial Capabilities Assessments (ICAs),[2] manufacturing management, producibility as part of technical reviews and audits, producibility analysis, Production Readiness Reviews (PRRs), and SPC.

Table 5-1. Producibility-Related SEP Requirements (mandatory) (sample)

Activity or Requirement	Planning and Timing
Manufacturing Management	Expectation: Updates at each milestone (example references may include MIL-HDBK-896, "Manufacturing Management Program Guide," SAE Standard AS6500, "Manufacturing Management Program," and FAA certified production system in accordance with 14 CFR Part 21, Certification Procedures for Products and Parts).
Industrial Capabilities Assessment (ICA)	Expectation: Updates at each Milestone (10 USC 4820 (formerly 2440))[3].
Technical Reviews and Audits	Expectation: Manufacturing inputs for each review and audit (SE Guidebook).
Producibility Analysis	Expectation: Describe approach (e.g., MIL-HDBK-727 or NAVSO P-3678 best practices).
Production Readiness Reviews (PRRs)	Expectation: PRR at system, subsystem, and component levels for prime and subcontractor (SE Guidebook).
Supplier Qualifications	Expectation: Description of approach (e.g., risk assessment, First Article Test/Inspection, audits, counterfeit parts mitigation).
Statistical Process Control (SPC)	Expectation: Applicable manufacturing processes are under SPC.
Quality Management and Assurance	Expectation: Updates for each phase of the program (example references may include applicable standards such as ISO 9000 and 9001 series and SAE AS9100 Quality Management Systems).
Contractor Oversight	Expectation: Description of Defense Contract Management Agency (DCMA) role to include quality oversight delegated to DCMA.

[2] The terms "Industrial Capabilities Assessment" and "Industrial Base Assessment" may be used interchangeably.
[3] As of January 2022, 10 USC was restructured with new section numbering.
https://www.acq.osd.mil/asda/ae/ada/title-10-reorganization.html

Required SEP content includes an assessment of manufacturing maturity. The SEP Outline states, “Describe the program approach to (1) assess manufacturing readiness as the program prepares to enter technical reviews and program milestones; and (2) Manufacturing Maturation Plans for Manufacturing Readiness Level (MRL) threads that are assessed below the target MRL criteria” (page 42) (see also DoD Manufacturing Readiness Level Deskbook and Section 6.1 of this guide).

Results are summarized as reflected in Table 3.2-6 of the SEP.

Table 5-2. Example SEP Table 3.2-6 Summary of MRA Results (mandatory)

Component, Subsystem, System Assessed	Assessment Description (Describe process, thread, or risk area from MRL Criteria)	Assessed MRLs			
		PDR Entry (Target MRL ≥ 6)	CDR Entry (Target MRL ≥ 7)	LRIP (Target MRL ≥ 8)	FRP (Target MRL ≥ 9)

5.4 M&Q Data

As best practice, M&Q practitioners should define, document, and provide input to the IPT to clearly state M&Q data requirements. This includes input to:

- Acquisition strategy.
- SEP, including digital engineering implementation plans.
- Contracting strategy and contract requirements (i.e., RFP, SOW, DIDs and CDRL).
- Product support management planning.

M&Q input should ensure requirements for product data and data rights are identified early in the life cycle, and appropriate contract provisions are in-place to enable timely, properly marked, and formatted data deliveries.

Per DoDI 5000.88, para 3.4a (3)(m), for Major Defense Acquisition Programs (MDAPs), ACAT II, and ACAT III programs, the SEP digital engineering implementation plan will contain these elements, unless waived by the SEP approval authority:

- Elements.
- Element relationship diagrams.
- Activity diagrams.
- Block definition diagrams.

- Use case diagrams.

DoDI 5000.88 further states, “The digital engineering implementation plan must include the evolution of a continuous end-to-end digital representation, or integrated set of digital representations, of the system being produced and the establishment of a digital authoritative source of truth (i.e., configuration controlled digital baseline). The PM will make the relevant digital model(s) accessible to OSD, Joint Staff stakeholders, and interdependent programs, throughout the life of the program and will maintain CM.”

Example M&Q data element needs are outlined below (Figure 5-3).

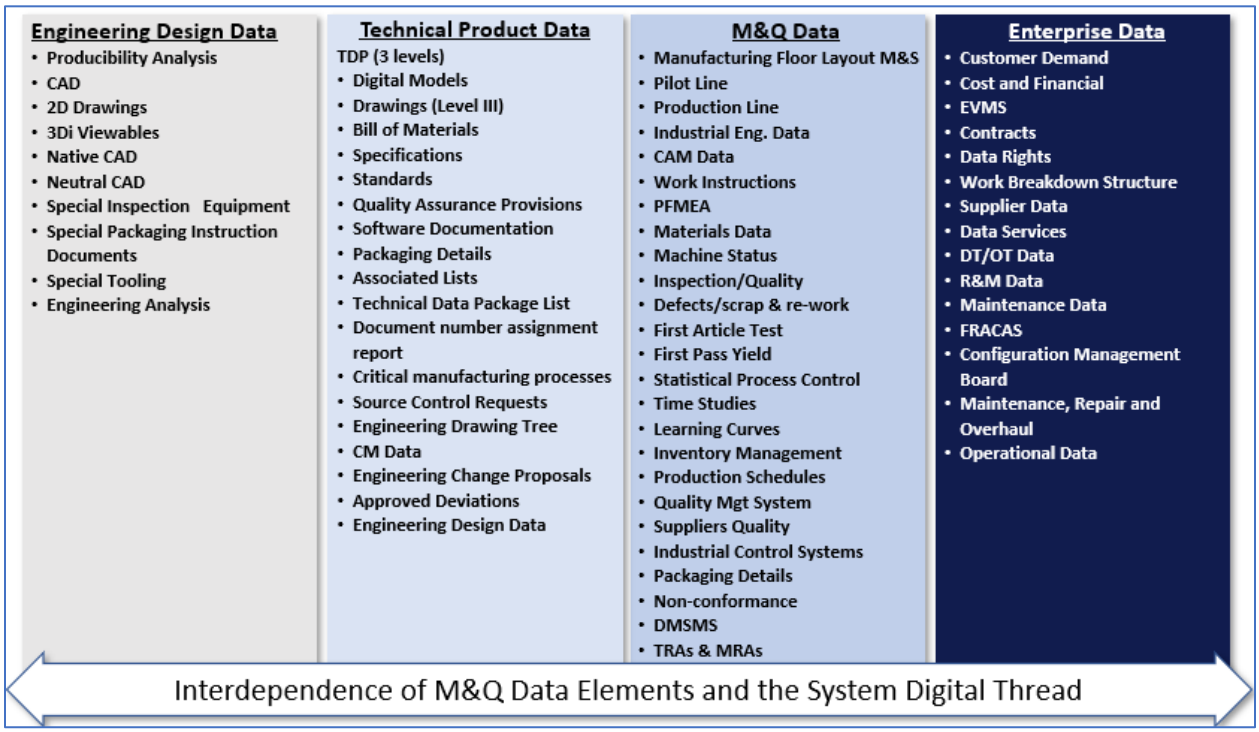


Figure 5-3. Example M&Q Data Element Needs

5.4.1 Product Life-cycle Management

Product Life-cycle Management (PLM) includes the process or system used for managing product-related design, production, and maintenance information. PLM systems are typically software applications designed for the purpose of life cycle management of a product.

To enhance the ease of manufacture, M&Q engineering specialists should actively engage in defining data requirements and data management approaches such as:

- Product Life-cycle Management (PLM).
- Integrated Digital Environments (IDE).

- Technical Data Package (TDP).
- Data formats.
- Contractual data rights.

5.4.2 Supply Chain Management Planning

Supply chain planning should occur as early as practical. This planning is important to ensure products from suppliers meet requirements. Early planning allows the prime contractor to consider processes for supplier selection, qualification, auditing, accepting product, and measuring compliance. As a best practice, M&Q practitioners should provide input for the IPT to determine what quality requirements will be flowed down to supply chain contractors. The prime contractor should manage subcontractors to an acceptable quality level, particularly for critical process, parts, and components from suppliers.

5.4.3 Technical Data Packages

As a best practice, M&Q practitioners should consult MIL-STD-31000 (current version) to define M&Q data requirements for the TDP. For production, a "Level III" TDP, or product-level TDP, consists of those TDP elements necessary to provide the design, performance requirements, engineering, manufacturing, inspection, packaging, and quality assurance provision information necessary to fully define the item that enables the procurement or manufacture of an item. A complete description is provided in MIL-STD-31000B, paragraph 5.14.4.

Key References

- DoDI 5000.88, Engineering of Defense Systems.
- DoDI 5000.97, Digital Engineering.
- MIL-STD-31000B, Technical Data Package.
- DoD Digital Engineering Strategy.

5.5 Value Engineering

As part of systems engineering activities, value engineering (VE) can support implementation of producibility enhancements. Standard Document 24 (SD-24), Value Engineering, defines VE as "…an organized/systematic approach that analyzes the functions of systems, equipment, facilities, services, and supplies to ensure they achieve their essential functions at the lowest life-cycle cost consistent with required performance, reliability, quality, and safety" (restated from IDA P-4114 2006).

DoD contracts should include a VE program implemented via a VE contract clause (reference Federal Acquisition Regulation (FAR) 48 and 52.248-1). In general, the VE program should

provide an incentive and opportunity for contractors to propose and implement producibility improvements (and other cost reduction initiatives) to reduce overall contract costs via a government and contractor savings sharing arrangement. Producibility cost savings and quality improvement initiatives are included in Value Engineering Change Proposals (VECPs) proposed by the contractor. Once the government provides technical approval, the VECP is incorporated by a contract change.

Key References

- DoDI 4245.14, DoD Value Engineering Program.
- SD-24, Value Engineering: A Guidebook of Best Practices and Tools.
- Office of Management and Budget, Value Engineering, Circular No. A-131, May 2013.

5.6 Producibility Improvement Program

As a best practice, project teams should establish a Producibility Improvement Program. Throughout the system life cycle, manufacturing practitioners should identify and advocate for producibility improvement opportunities. When not able to incorporate producibility features and processes during detailed system design, practitioners should still pursue opportunities to improve ease of manufacturing. These activities may be identified throughout the system life cycle, and opportunities to plan, budget, and implement producibility improvements should continue during manufacturing operations. Producibility improvement approaches can be developed and tailored to each program based on available resources, schedule, production quantities, and return on investment. MIL-HDBK-896A recommends formal Producibility Improvement Programs and provides a suggested approach as follows:

Producibility Effort Targets

To determine where to target producibility efforts, assemblies can be evaluated using some or all of the following characteristics:

- Assemblies with high realization factor.
- Assemblies that are time-consuming or difficult to assemble.
- Assemblies consisting of many parts.
- Assemblies consisting of expensive or difficult-to-manufacture parts.
- Assemblies or parts that have experienced excessive failures in the field, which possibly could be improved by a more robust design.
- Assemblies that required significant use of redlines in work instructions.
- Areas having a high cost of quality.
- Assemblies with many shims.

Producibility Improvement Programs should be formally documented to include the baseline (before implementation) costs and post-implementation costs, as well as the non-recurring costs to implement the initiative. It is often difficult to distinguish initiatives that are "over and above" the historical learning curves that were already used to estimate the program costs. Historical learning curves usually include some amount of cost reduction initiatives, so the challenge in documenting and estimating the impacts of new projects is to determine if they are truly over and above what has been done in the past. Generally, initiatives that reduce the scope of work can be considered over and above, but the ones that improve the efficiency of the work must be more carefully evaluated (MIL-HDBK-896A).

Key Reference

- MIL-HDBK-896, Manufacturing Management Program Guide

5.7 Risk, Issue, and Opportunity

M&Q specialists should provide the IPT with producibility input to the program Risk, Issue, and Opportunity (RIO) management processes and participate in the Risk Review Board or Risk Management Board. Producibility RIOs should also be included in the SEP. M&Q responsibilities include:

- Report and identify producibility risks or issues.
- Recommend criteria used to determine whether a potential producibility risk submitted for consideration becomes a risk tracked by the Risk Management Board (i.e., criteria for likelihood and consequence).
- Track, add, or modify risks.
- Change likelihood and consequence of a risk.
- Close a risk or issue.

In addition to producibility analysis techniques, Manufacturing Readiness Assessments using the MRL Deskbook and criteria, as discussed in section 6.1.5, provide a best practice and structured approach to provide M&Q input to the program RIO management process.

Key Reference

- DoD Risk, Issue, and Opportunity (RIO) Management Guide for Defense Acquisition Programs.

5.8 Producibility Plan

As part of producibility planning and as a best practice, the government's RFP should require the contractor to develop and submit a Producibility Plan for government approval that outlines the contractor's approach to producibility. The plan should be updated throughout the life cycle to indicate status against the plan. Appendix E provides suggested topics that should be addressed in the contractor's plan.

Key References

- SAE AS6500 Manufacturing Management Program.
- DoD Systems Engineering Plan Outline, Version 4.1.
- MIL-HDBK-896, Manufacturing Management Program Guide.
- Data Item Description DI-MGMT-81889B, Manufacturing Plan.
- Data Item Description DI-MGMT-80797A, Producibility Analysis Report.

6 PRODUCIBILITY: CONCURRENT ENGINEERING

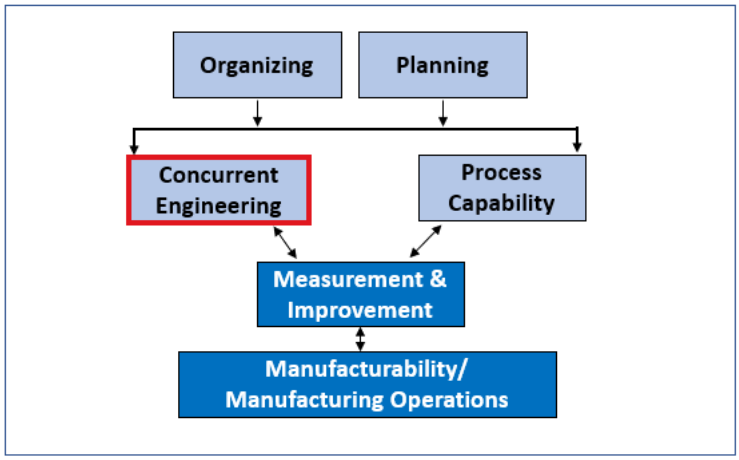


Figure 6-1. Major Producibility Activities—Concurrent Engineering

DAU defines concurrent engineering as, "A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. Concurrent engineering activities, indicated in red (bold outline) in Figure 6-1, will be discussed in this section. Concurrent engineering is intended to cause developers, from the beginning, to consider all elements of the system life cycle from requirements development through disposal, including cost, schedule, and performance."

Although producibility engineering is not a specified engineering discipline, DoD MIL-HDBK-727 recognizes producibility as an inherent job element of development teams with shared responsibilities. The producibility concept of concurrent engineering refers to this relationship. As a best practice, manufacturing personnel should influence the design, and they should provide producibility input for consideration by the IPT during all SETRs throughout the system life cycle. This section describes producibility activities relevant to program engineering as the system progresses through the development and detailed design process. In addition, Appendix A includes a summary of common producibility-related tools to support concurrent engineering.

6.1 System Concept and Early System Development Producibility Activities

Project technical teams and IPTs should include producibility considerations starting with the earliest phases of the system life cycle. For the MCA pathway, considering producibility begins during Pre-Milestone A as system concepts are being developed with the Pre-Materiel Development Decision (Pre-MDD), MSA, and Technology Maturation and Risk Reduction (TMRR) phases. Early producibility-related analyses include the following:

- Manufacturing Feasibility Assessment.
- Industrial Base Assessment.

- Manufacturing Readiness Level Assessment (also referred to as Manufacturing Readiness Assessment (MRA))
- Input to the Analysis of Alternatives (AoA), Alternative Systems Review (ASR), System Requirements Review (SRR), and System Functional Review (SFR).

Additional information on manufacturing activities and tasks during early system development can be found in the DoD Early Manufacturing and Quality Guide and the DoD Manufacturing and Quality Body of Knowledge.

6.1.1 Manufacturing Feasibility Assessments

A Manufacturing Feasibility Assessment (MFA) (or Manufacturing Feasibility Estimate) is a holistic analysis and early evaluation of the practicality of a proposed solution for future production. The program team, with manufacturing leadership and input, conducts the assessment to recommend whether the proposed concept is feasible and should move forward. As a best practice, the program team should conduct MFAs beginning with alternative concept trade studies during the Pre-MDD and MSA phases.

A key objective of the MFA is to narrow the range of early system concept solution approaches under consideration by identifying the most feasible alternatives. The assessment should address operational, technical, economic, and schedule feasibility.

The feasibility estimate determines the likelihood that a proposed materiel solution can be produced using existing manufacturing capabilities while meeting quality, production rate, and cost requirements. The analysis involves the evaluation of:

- Producibility of the potential design concepts.
- Critical manufacturing processes and special tooling development that will be required.
- Test and demonstration required for new materials.
- Anticipated manufacturing risks and potential cost and schedule impacts.

An MFA answers the question, “Can the system be manufactured at the required rates, quantities, and cost objectives to meet the customers’ requirements?”

Producibility should be part of the MFA. The early assessment may address the following questions:

- Is the product adequately defined to enable an assessment?
- Is the design reproducible within known or anticipated manufacturing capabilities?
- Are required materials available?

This information is the basis for manufacturing input to the AoA and may represent one of the best early opportunities to influence producibility.

As the system becomes more defined, or the concept approach is using mature technologies (i.e., Urgent Capability Acquisition), the MFA may address the following:

- Can the product be produced to the tolerances specified in the technical data package?
- Are the manufacturing processes to be used stable and in control?
- Can the product be produced to the appropriate process capability requirements?
- Do available facilities have the capacity to meet production requirements?
- Do manufacturing personnel have the appropriate training, skills, and certifications for all tasks?
- Can the product be produced based on the estimated cost or budget constraints?
- Has a learning curve been established for new processes?
- Can the product be produced to the planned schedule?
- Has a line of balance or critical path been established for production?
- Have appropriate test requirements and qualifications been identified to adequately characterize materials and performance?
- Is the supply chain in place and capable of meeting contract requirements?

If the assessment identifies gaps, the technical team, with manufacturing input, can suggest approaches to close producibility gaps (e.g., additive manufacturing, factory floor modeling and simulation, robotics, adaptive machining) or investments such as Independent Research and Development (IRAD) projects, the DoD Manufacturing Technology (ManTech) Program (DoDI 4200.15 Manufacturing Technology Program), Industrial Base Analysis and Sustainment (IBAS), and Defense Production Act Title III program.

In particular, the DoD ManTech Program provides DoD development teams with opportunities to develop advanced manufacturing technologies and processes to address producibility gaps and risks.

6.1.2 Industrial Capabilities Assessment

An ICA is an assessment of the ability of the supplier base to produce the required items. Starting with early concept development (Pre-MDD), manufacturing personnel should characterize the industrial base capability for the types of commodities expected to solve the warfighters' needs.

Early ICA objectives include:

- Identify anticipated industrial base and supply chain.
- Identify the supply chain capability and capacity to produce and confirm the financial stability of key suppliers.
- Identify industrial base capability risks such as single points of failure and unreliable suppliers (i.e., single source, sole source, foreign source, and diminishing manufacturing sources and material shortages (DMSMS)).
- Assess the industrial base ability to successfully transition prototype systems to production and the ability to meet program quantities, rates, and quality requirements to deliver and sustain operational systems.

The M&Q lead should consider requesting assistance from the Defense Contract Management Agency (DCMA) Industrial Analysis Division to identify, analyze, and assess the supply chain.

DoDI 5000.85, Major Capability Acquisition, requires the ICA or Industrial Base Assessment (IBA) results to be documented in acquisition planning and included in the program Acquisition Strategy (AS). In accordance with 10 United States Code (USC) 4820 (formerly 2440), the ICA or IBA is required to be updated at each milestone.

When the ICA identifies potential industrial base producibility gaps, risks, issues, or opportunities, the M&Q lead should consider coordinating with the Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD(A&S)) IBAS program for potential mitigation. For example, the IBAS program may provide resources or make industrial base investments to obtain or preserve unique or unavailable production capabilities. Information on DoD industrial programs can be found at https://www.businessdefense.gov. Examples:

- The IBAS program enables investments to monitor and assess the industrial base, address critical industrial base issues related to urgent operational needs, expand the industrial base, and address supply chain vulnerabilities (10 USC Section 2508, “Industrial Base Fund”).

- Defense Production Act Title III provides the authorities to create, maintain, protect, expand, or restore domestic industrial base capabilities (50 USC 55, “Defense Production Act,” Chapter 55, Title III, “Defense Production,” 1950).

The M&Q lead should also consider government, academic, industry, or other resources to address gaps. The following are example opportunities for manufacturing capability development throughout the entire system life cycle:

- The DoD Manufacturing Technology Program (DoDI 4200.15) focuses on the development and application of advanced manufacturing technologies and processes that will reduce the acquisition and sustainment manufacturing/repair cycle times and cost.

- Manufacturing Innovation Institutes (MIIs): The OUSD(R&E) Manufacturing Technology Program oversees DoD MIIs focused on connecting organizations and activities to better enable the affordable, rapid transition and delivery of essential defense technologies. The DoD MIIs are part of Manufacturing USA, which unifies a network of agency-sponsored MIIs that offer opportunities for partnership with DoD, Department of Energy, Department of Commerce, industry, and academic engineering activities on applied manufacturing research across a broad spectrum of advanced manufacturing technologies.
- Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) offer competitive programs focused on encouraging small businesses to participate in federal research and development (R&D) programs with commercial potential.
- Defense Innovation Unit (DIU) provides opportunities to adopt commercial technologies to rapidly prototype and field commercial solutions.
- Defense Advanced Research Projects Agency (DARPA) invests in breakthrough technologies for national security.
- Service and Federal research laboratories conduct research, technology development, prototyping, and cutting-edge research to develop and transition specialized technical capabilities.
    - U.S. Army Research Laboratory.
    - U.S. Naval Research Laboratory.
    - U.S. Air Force Research Laboratory.
    - U.S. Coast Guard Research and Development Center.
    - Rapid Capability Offices (RCO) (i.e., Army (Rapid Capabilities and Critical Technologies Office), Navy, Air Force, Marine Corps RCOs).
    - Service Prototype Integration Facilities and rapid prototyping activities.
    - FFRDCs—public-private partnerships to conduct R&D for the U.S. Government.
- The National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership, a public-private partnership to serve small- and medium-size manufacturers, provides opportunities for collaboration on manufacturing technology development.
- IRAD provides opportunities for industry investment to develop technology of interest to both industry and government (i.e., manufacturing cost reduction, quality improvements).

Key References

- DoDI 5000.60, Defense Industrial Base Assessments.
- DoD Handbook 5000.60H, "Assessing Defense Industrial Capabilities," April 1996.
- DCMA-INST-3401, Defense Industrial Base Mission Assistance.
- DCMA Manual 3401-05, Defense Industrial Base Monitoring and Reporting.
- DoD Directive 4200.15, Manufacturing Technology (ManTech) Program.

6.1.3 Independent Technical Risk Assessments

Per 10 USC 2448b (renumbered 4272) (FY17 National Defense Authorization Act (NDAA) Sections 807 and 808), the following are required at Milestone A:

> "Submissions to Congress on Milestone A—(1) Brief Independent Technical Risk Assessments (ITRA) summary report.—Not later than 15 days after granting Milestone A approval for a major defense acquisition program, the MDA should provide to the congressional defense committees…a brief summary report that contains the following elements:
>
> > A summary of the technical or **manufacturing risks** associated with the program, as determined by the military departments concerned, including identification of any critical technologies or **manufacturing processes that need to be matured.**
> >
> > A summary of the independent technical risk assessment conducted or approved under Section 2448b of this title, including identification of any critical technologies or **manufacturing processes that need to be matured."**

For Major Defense Acquisition Programs (MDAPs), before each milestone decision (MS A, B, C, Low-Rate Initial Production (LRIP), Full-Rate Production (FRP), an ITRA is required. The ITRA approval authority must be independent and may not be in the program's chain of command. The project technical team should be aware that they may need to support and participate in ITRA activities beginning prior to Milestone A.

DoDI 5000.88, Engineering of Defense Systems, states an ITRA will

> consider the full spectrum of technology, engineering, and integration risk. These areas could include mission capability, technology, system development, MOSA (Modular Open Systems Approach), software, security, manufacturing, sustainment, and their potential impacts to cost, schedule, and performance. For ITRAs conducted before Milestone A, identifies critical technologies and manufacturing processes that need to be matured. Subsequent ITRAs will re-assess technology and manufacturing process maturity, accounting for demonstrations in relevant environments. (page 17)

DoDI 5000.88 states that OUSD(R&E) is the ITRA approval authority for ACAT ID programs and determines ITRA approval authority for ACAT IB/IC programs. ITRAs are not required for non-MDAP programs, but if conducted, they should follow the OUSD(R&E) ITRA guidance. The Defense Technical Risk Assessment Methodology (DTRAM) defines ITRA assessment criteria and categories (OUSD(R&E) DTE&A).

Key References

- 10 USC 2448b (FY 2017 National Defense Authorization Act (NDAA) Sections 807 and 808) (renumbered 10 USC 4272).
- DoDI 5000.88, Engineering of Defense Systems.
- Defense Technical Risk Assessment Methodology.

6.1.4 Diminishing Manufacturing Sources and Material Shortages

Per DoDI 4245.15, Diminishing Manufacturing Sources and Materials Shortages Management, it is DoD policy to evaluate all DoD system designs and redesigns for potential DMSMS issues that could arise during the life cycle of DoD items. DoDM 4245.15, Management of Diminishing Sources and Material Shortages, specifies that a program office's DMSMS management plan should ensure design decisions consider DMSMS resilience. DoDM 4245.15 defines DMSMS resilience in system design as follows:

> The use of design techniques that reduce the likelihood of near-term DMSMS issues and increase the probability of a quick recovery when issues do occur. DMSMS resilience is incorporated into a design by applying a modular, open system approach along with other supportability-related design considerations. This must be done in conjunction with part selection procedures that choose items with significant time left in their life cycle and with viable replacement options whenever possible. (page 38)

Additional best practices can be found in the SD-22, Diminishing Manufacturing Sources and Material Shortages, A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program.

In addition to DMSMS considerations for product design and redesign(s) and as a best practice, the IPT should manage DMSMS and obsolescence for the entire manufacturing and sustainment ecosystem, for example, for manufacturing equipment, machines, tooling, special test equipment, and special inspection equipment.

Key References

- DoDI 4245.15, Diminishing Manufacturing Sources and Materials Shortages Management.

- DoDM 4245.15, Management of Diminishing Sources and Material Shortages.
- SD-22, Diminishing Manufacturing Sources and Material Shortages, A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program.
- SD-26, DMSMS and Parts Management Contracting Guide.
- SD-19, Parts Management Guide.
- MIL-STD-11991B, DoD Standard Practice General Standard for Parts, Materials, and Processes.
- DI-STDZ-81993, Parts, Materials, and Processes Management Plan.

6.1.5 Manufacturing Readiness Level Assessments and Technology Readiness Assessments

While not a specific measure of producibility engineering, Manufacturing Readiness Levels (MRLs) include readiness and risk assessment criteria and assessment of producibility considerations. MRLs provide qualitative assessments (scale of 1-10) as summarized in Table 6-1. MRL assessments are a recommended best practice for IPTs throughout the entire system life cycle. This assessment approach is introduced in this section but is applicable to all program phases (see also MRL Body of Knowledge website).

Table 6-1. MRL Descriptions

MRL	Description
MRL 1	*Basic manufacturing implications identified*. This level is generally characterized as basic research (budget activity 6.1) and is often in the form of a study.
MRL 2	*Manufacturing concepts identified*. Activities at this level tend to be applied research (budget activity 6.2), which is basic research focused into solutions for broadly defined military needs.
MRL 3	*Manufacturing proof of concept developed*. Also known as Applied Technology Development (budget activity 6.3). At this stage, materials and/or processes have been characterized for manufacturability and availability. Experimental hardware models have been developed in a lab environment that may possess limited functionality.
MRL 4	*Capability to produce the technology in a laboratory environment*. Manufacturing processes have been identified along with key processes. Producibility assessments have begun.
MRL 5	*Capability to produce prototype components in a production-relevant environment*. Manufacturing processes are beginning to emerge. Producibility assessments are ongoing and manufacturing cost drivers have been identified.
MRL 6	*Capability to produce a prototype system or subsystem in a production-relevant environment*. Manufacturing processes are now being demonstrated in a relevant environment. Manufacturing cost drivers have been analyzed and long lead items have been identified. Production equipment is in a relevant environment.
MRL 7	*Capability to produce systems, or subsystems, or components in a production representative environment*. Manufacturing processes are in development and producibility improvements are under way. Trade studies are being conducted having manufacturing implications, and supply chain management practices are in place.

MRL	Description
MRL 8	*Pilot line capability demonstrated; ready to begin low-rate initial production [LRIP]*. Manufacturing process maturity is being demonstrated on a pilot line. All materials are ready for LRIP. Manufacturing processes are now proven, and the supply chain is stable for LRIP.
MRL 9	*Low-rate production demonstrated; capability in place to begin full rate production [FRP]*. Manufacturing processes are operating at target quality, cost, and performance goals. The supply chain is established and meeting lead times, cost, and performance objectives.
MRL 10	*Full-rate production demonstrated and Lean production practices in place*. The manufacturing is mature and is meeting FRP goals. Lean Six Sigma practices have been put in place and are reaping benefits. The program is meeting or exceeding (in a positive way) cost, schedule, and performance goals.

The MRL assessment criteria matrix includes topics for the assessment team in categories referred to as MRL "threads" and "sub-threads." Threads and sub-threads include criteria and areas for assessment. Starting with MRL1, where basic manufacturing implications are identified, MRL assessments include a series of questions and considerations to assess development and implementation of the producibility program. Producibility as a design consideration is addressed primarily in "Thread B – Design," and sub-thread B.1 "Producibility Program." There are producibility-related criteria for all MRLs (i.e., MRLs 1-10).

The MRL criteria matrix also includes other producibility and manufacturability-related considerations. Examples include:

- Thread C – Cost & Funding.
- Sub-thread C.2 – Cost Analysis.
- Sub-thread D.2 – Availability of Materials (DMSMS). DMSMS resilience should also be addressed by the IPT as part of producibility design considerations in Thread B – Design.
- Thread I – Manufacturing Management.
- Sub-thread I.3 – Manufacturing Operational Technology Cybersecurity.

As a best practice, M&Q practitioners should conduct periodic MRL assessments, and when needed take action to mitigate producibility risks. The government program office team should lead assessments at the prime contractor. When the prime contractor conducts assessments at suppliers, the government should participate. The government should not rely on assessments performed only by the contractor without government insight.

Technology Readiness Assessment (TRA): A TRA is a systematic, metrics-based technical assessment process using Technology Readiness Levels (TRLs) to assess the maturity and risks associated with critical technologies. During system development, technical teams often focus on technology maturity and conduct TRAs.

TRLs are used to assess the maturity of technologies from a performance perspective. System development IPTs and IPTs conducting producibility planning, engineering, and assessments

should recognize that TRLs do not address transition to production, producibility, or manufacturability issues. Therefore, manufacturing personnel should proactively request the IPT conduct MRL assessments and update the assessment at each SETR.

Key References

- Manufacturing Readiness Level Deskbook, MRL Working Group.
- Technology Readiness Assessment (TRA) Guidebook.

6.1.6 Analysis of Alternatives and Producibility

In conducting and completing the AoA, the program team analyzes various alternative solutions for trades among affordability analyses, risk analyses, and planning for risk mitigations that have an impact on cost, schedule, and performance. Development of the AoA is an ideal opportunity to provide early producibility inputs to the system concept development process, which will guide both the AoA and MSA phase (MCA pathway) activities. The AoA will address manufacturing feasibility and technology maturity of the alternatives, to include the following, all of which affect producibility:

- Risks, issues, and opportunities associated with varying production rates.
- Manufacturing skill requirements.
- Maturity of new materials and novel processing methods.
- The state of the following factors:
    - Industrial base capabilities.
    - Manufacturing technology research.
    - Facilities and tooling.
    - Special test equipment and special inspection equipment.

For example, the industrial base capability assessment, outlined in section 6.1.2, should feed into the AoA to determine whether or not different manufacturing methods can achieve the same requirements. Depending upon the initial design of the product, the drawings may force suppliers to use a specific manufacturing method. These drawing requirements may artificially constrain the industrial base and result in either sole source or quality risks and issues. Manufacturing methods such as forging require the use of draft angles and additional post operations machining with a limited and shrinking forging industrial base. If designs can be optimized to use additional methods such as lathe or mill work, the base of potential vendors may increase, allowing the DoD to take advantage of competition to control cost.

Another purpose of the AoA is to identify new or high-risk manufacturing capabilities or capacity requirements that might be needed. The analysis also identifies critical technologies and their associated manufacturing process areas that might merit some development work to reduce risk of selecting that approach. When a contractor performs the AoA, the Government IPT should review the AoA for these considerations.

Starting with early system development (AoA, SRR, and SFR), the IPT should use Six Sigma tools to assist with producibility considerations. As an example, Quality Function Deployment (QFD) is a tool to analyze customer requirements and to conduct system trade-off studies. As the system is further defined, QFD provides useful producibility information as subsystems, components, and processes are developed.

Key References

- DoDI 5000.84, Analysis of Alternatives.
- *The Lean Six Sigma Pocket Toolbook*, McGraw-Hill, 2005.

6.2 Systems Engineering Technical Reviews During Concept Development

The DoD Systems Engineering Guidebook describes SETRs and audits. In addition, Institute of Electrical and Electronics Engineers (IEEE) 15288, Standard for Technical Reviews and Audits on Defense Systems, further defines technical review and audit activities and outputs throughout the acquisition life cycle (Figure 6-2). The IPT should refer to authoritative guidance and standards for details of SETR processes. The following sections focus on producibility and manufacturability considerations during the SETR process and audits.

For description and illustration, sections 6.2 through 6.4 apply to the MCA pathway. Producibility and manufacturability efforts should be tailored for other pathways and program-unique requirements.

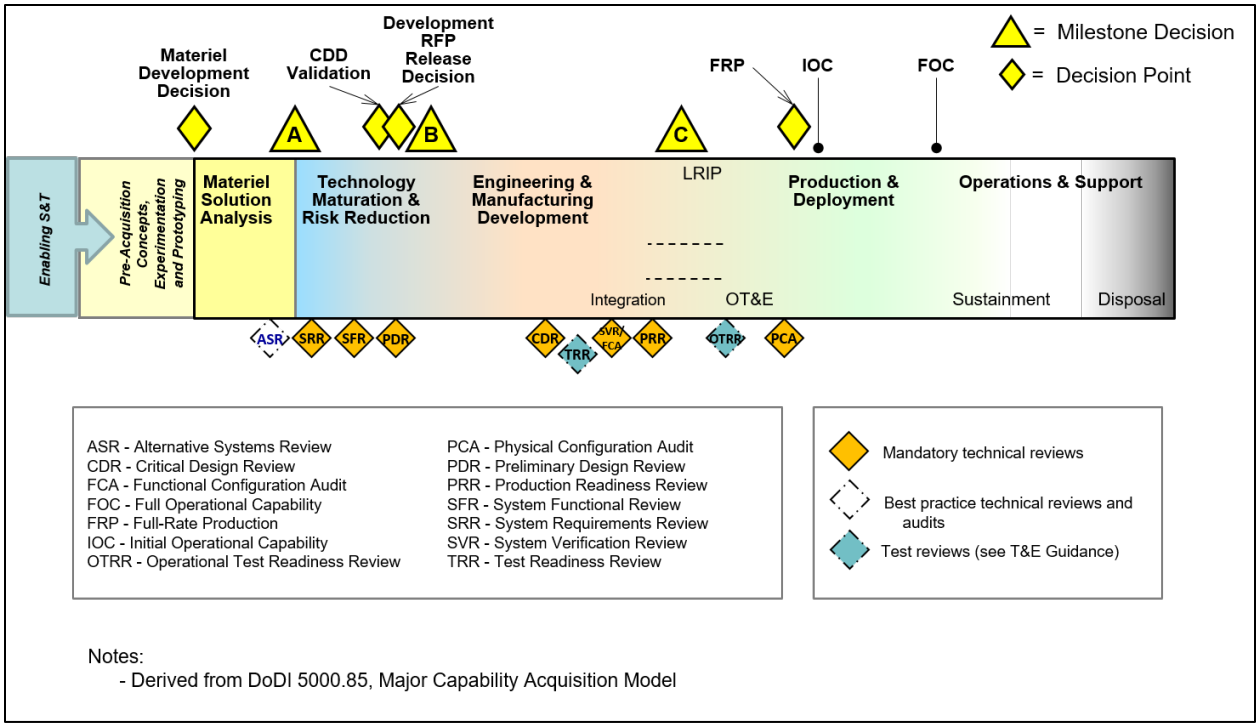


Figure 6-2. Technical Reviews and Audits for the MCA Life Cycle

6.2.1 Alternative Systems Review

The purpose of the Alternative Systems Review (ASR) is to review the technical and programmatic plans (including the SEP) to transition the preferred system concept, down-selected during the AoA process, to ensure the concept is ready to proceed into the next phase. The ASR technical team should include producibility considerations such as items identified in Table 6-2.

Table 6-2. ASR and Producibility Considerations

Producibility Area	Alternative Systems Review (ASR) Considerations
Producibility Planning	• Participate in Analysis of Alternatives (AoA) and provide inputs to the draft Capability Development Document. • Provide inputs to the draft Acquisition Strategy and Systems Engineering Plan and develop initial manufacturing strategies and plans. • Support development of the draft Requests for Proposal, review contractor proposals, and support cost estimating and tracking. • Assess projected production rates and quantities. • Develop manufacturing and quality strategies to include approach to production (e.g., co-production, leader-follower, foreign production, organic industrial base, defense industrial base) • Assess required and projected production capacity and yield rates. • Identify manufacturing cost drivers.

Producibility Area	Alternative Systems Review (ASR) Considerations
	• Perform initial producibility and manufacturability assessments for selection of preferred materiel solution. Ensure results are considered in the AoA and documented in the Acquisition Strategy.
Producibility Engineering	• Provide manufacturing input on trade studies and technical demonstrations. • Conduct a manufacturing review of trade studies and technical demonstrations results, if available. • Participate in Integrated Product Team to obtain clear understanding of the system requirements. • Ensure the draft system performance specification has sufficiently conservative requirements to allow for design trade space. • Establish relationship between draft system performance specification and risk reduction prototyping and competitive prototyping objectives. • Identify potential manufacturing cost drivers. • Develop initial producibility assessments of solution concepts. • Conduct initial Manufacturing Feasibility Estimate. • Conduct initial Industrial Capabilities Assessment. Updates as required at each milestone per 10 USC 4820 (formerly 2440). • Assess materials requirements to include potential risk areas (i.e., materials availability, long lead, sole source, foreign source, potential DMSMS). • Identify hazardous materials embedded in the system or used in manufacturing processes. • Identify initial producibility technical risks and initiate mitigation plans. • Conduct early Manufacturing Readiness Level assessment. • Provide manufacturing input to the program data architecture. • Assess and define manufacturing data rights requirements. • Provide input to the Product Life-cycle Management approach.
Process Capability	• Determine process capability for known processes such as modification or reuse of existing systems. Project process capability requirements for anticipated manufacturing processes. • Conduct projected and actual process capability studies using process performance index and process capability index. • When possible, use Statistical Process Control techniques to determine stable and variable processes.

6.2.2 System Requirements Review

Scheduled at the beginning of the Technology Maturation and Risk Reduction (TMRR) phase, the System Requirements Review (SRR) is a multidisciplined technical review designed to communicate system requirements to developers. An SRR assesses whether the system requirements (embodied in the System Requirements Document (SRD)) are consistent with the preferred materiel solution and technology maturation plans. It assesses whether all requirements derived from the SRD are defined and consistent with cost, schedule, and risk limitations.

The numerous studies and analyses performed during the SRR provide multiple opportunities to assess and measure producibility. Areas relevant to producibility efforts include:

- System/cost-effectiveness analysis.
- Trade-off studies.
- Program risk analysis.
- Producibility analyses performed and planned.
- Engineering integration.
- Life cycle cost analysis.

The SRR builds upon assessments and activities performed for the ASR and then extends them further by providing both qualitative and quantitative assessments of producibility, as well as other design and manufacturing attributes. Example SRR producibility considerations are included in Table 6-3.

Table 6-3. SRR and Producibility Considerations

Producibility Area	System Requirements Review (SRR) Considerations

Producibility Planning	• Manufacturing personnel proactively participate in IPT technical activities as the functional baseline, performance specifications, and system requirements are established and trade studies and risk assessments are conducted.
	• Review contractor SEMP to ensure producibility is adequately addressed.
	• Manufacturing engineering is properly staffed.
	• Manufacturing program is executable within the existing budget.
	• Review and update.
	  o Identification of manufacturing cost drivers.
	  o Initial producibility assessments of solution concepts.
	  o Initial Manufacturing Feasibility Estimate.
	  o Initial Industrial Capabilities Assessment.
	  o Initial assessment of materials requirements and gaps (i.e., materials availability, long lead, sole source, foreign source, DMSMS).
	• Initiate supply chain management planning.
	• Update Manufacturing Readiness Level assessment.
	• Planning has begun for the creation of a digital engineering ecosystem to include manufacturing and producibility data, and the planning is captured in the SEP and in other appropriate program plans.
	• The manufacturing and production strategy is complete and adequate.

Producibility Engineering	• Assess manufacturing feasibility and capability to produce in a lab environment. • Program critical technologies are ready for the TMRR phase.

Producibility Area	System Requirements Review (SRR) Considerations
	• Required investments in manufacturing technology development have been identified. • Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce prototypes. • Manufacturing risks and mitigation plans are in place for building prototypes. • Cost objectives have been established and manufacturing cost drivers have been identified; draft key characteristics have been identified as well as any special tooling, facilities, material handling and skills required. • Derive initial TPMs. • Select DMSMS resilient parts. • Producibility assessment of the preferred system concept has been completed, and the industrial base capabilities, current state of critical manufacturing processes and potential supply chain sources have all been surveyed. • Potential DMSMS risks assessed. • Review and update assessment of manufacturing data rights requirements. • Manufacturing input to the program data architecture.
Process Capability	• Determine process capability for known processes (such as modification or reuse of existing systems). Project process capability requirements for anticipated manufacturing processes. • Conduct projected and actual process capability studies using process performance index and process capability index. • When possible, use SPC techniques to determine stable and variable processes.

6.2.3 System Functional Review

The System Functional Review (SFR) examines the functional baseline to determine if it satisfies the specified end-user requirements and capability needs. It is typically at the completion of SFR that the functional baseline comes under configuration control.

A functional baseline defines a system's performance (functional, interoperability, and interface) to meet specification characteristics. The functional baseline is directly traceable to the operational requirements. The SFR is used to:

- Assess whether a balanced definition of the system's major elements has been developed.
- Assess whether the functional baseline is achievable regarding cost, schedule, and performance.
- Confirm that the system performance specification (typically put on contract) is realistic.
- Provide a sound technical foundation for preliminary design.

Example SFR producibility considerations are included in Table 6-4.

Table 6-4. SFR Products and Producibility Criteria

Product	System Functional Review (SFR) Considerations

Producibility Planning	• Manufacturing personnel proactively participate in IPT technical activities as the functional baseline, performance specifications, and system requirements are established, and trade studies and risk assessments are conducted.
	• Producibility risks identified and documented.
	• Review and update.
	  ○ Identification of manufacturing cost drivers.
	  ○ Initial producibility assessments of solution concepts.
	  ○ Initial Manufacturing Feasibility Estimate.
	  ○ Initial Industrial Capabilities Assessment.
	  ○ Initial assessment and gap-closing strategy for materials requirements (i.e., materials availability, long lead, sole source, foreign source, DMSMS).
	• Establish the Process Failure Modes and Effects Analysis (PFMEA) team.
	• Update Manufacturing Readiness Level assessment.

Producibility Engineering	• Ensure design consideration documents include producibility. • Define producibility engineering guidelines. • Establish detailed producibility plan and schedule, sufficiently resourced to continue input to design and development IPT. • Ensure producibility engineering consideration plans and activities have been integrated into the program plan, as appropriate. • Ensure contractor producibility requirements are specified in the Statement of Work (SOW) and Request for Proposal. • Initiate process to evaluate the design for Key Characteristics and Critical Characteristics. • Initiate process to evaluate and identify critical manufacturing processes. • Provide manufacturing input to the program data architecture. • Initial PFMEA analysis. • Conceptual Level Technical Data Package developed. • Update assessment of manufacturing data rights requirements. • M&Q input to PLM approach.
Process Capability	• Conduct projected and actual process capability studies using process performance index and process capability index. • Use SPC techniques to determine stable and variable processes.

6.3 Detailed Design and Producibility

As a best practice, the M&Q practitioners' role during the detailed design process is to influence the design so it is producible. Design engineers need to understand and consider many factors including factory floor capabilities and capacities if they are to achieve cost goals.

DoDI 5000.88 states, "During the Engineering and Manufacturing Development (EMD) phase, the PQM lead will advise the PM on the maturity of critical manufacturing and quality processes to ensure they are affordable and executable" (page 22).

This section outlines producibility engineering approaches and considerations during the detailed design process, culminating at the PDR and Critical Design Review (CDR). Designing for producibility begins with Producibility Engineering Planning (PEP) and the use of producibility engineering tools and techniques:

- Design guidelines.
- Process capability guidelines and process capability benchmarking.
- Design for Manufacturability and Assembly (DFMA) analyses.
- Design for Ergonomics (DFE) for manufacturing processes and workforce.
- Process Failure Modes and Effects Analysis (PFMEA).
- Identification of Key Characteristics and Critical Characteristics.
- Identification of critical manufacturing processes.
- Modeling and simulation (M&S) tools.
- Rapid prototyping.
- Product and process complexity analyses.
- Diminishing Manufacturing Sources and Material Shortages planning.
- Six Sigma tools.

Key References

- DoD Systems Engineering Guidebook.
- Best Practices for Using Systems Engineering Standards (ISO/IEC/IEEE 15288, IEEE 15288.1, and IEEE 15288.2) on Contracts for Department of Defense Acquisition Programs, DoD, April 2017.

6.3.1 Producibility Design Guidelines

As described in Section 2, the principles of producibility provide general design objectives to enhance ease of manufacture. General design guidelines are outlined in Table 6-5; however, detailed design for producibility may involve complex design considerations and trade-offs.

Table 6-5. Sample General Design Best Practices

General Design Best Practices
• Simplify the design. • Design for low labor cost (i.e., tumble deburring requires less labor than hand deburring). • When possible, avoid secondary operations. Consider the cost to eliminate or simplify operations such as deburring, plating, heat treating, and material handling (i.e., overhead crane operations). • Avoid generalized statements in drawings. • Dimensions should be from one datum line to simplify gaging and tolerance calculations. • Lighter parts are generally lower cost. • Whenever possible, use general purpose tools versus special tooling. • Avoid sharp corners – applicable to castings, molded, formed, and machined parts. • Avoid thin wall conditions when possible. • Avoid repositioning the part during the manufacturing process. • Space holes in machined, cast, and molded process so parts can be made in one operation. • Keep castings and molded parts wall thickness uniform when possible.

Source: Derived from “Design for Manufacturability Handbook” (Bralla 1986).

When establishing a producibility program, the IPT needs to define and implement producibility design guidelines. These guidelines can range from simple recommendations to detailed methods, metrics, Geometric Dimensioning and Tolerancing (GD&T), and design criteria. These guidelines should provide the design team with design parameters, best practices, and technical information to avoid known producibility and manufacturing mistakes.

Manufacturing technologies, processes, and materials contribute to a vast knowledge base and are evolving rapidly. In addition to the design teams’ knowledge and experience, many design guidelines are available to research specific design criteria and options for the application being considered. Since each product consists of many different attributes, these guidelines include a multitude of detailed manufacturing processes, materials selection, geometries, dimensions, and tolerances and may require extensive engineering analysis.

In addition, design for manufacture guidelines should consider the processes and capabilities of the manufacturing industry. Depending on the product manufacturing technologies (e.g., automation, miniaturization, micro-electronics, and advanced materials), the design team may require access to the latest technical information and design guidelines.

Key References

- *Design for Manufacturability Handbook*, *Second Edition*, James G. Bralla, McGraw-Hill, 1986 (includes thousands of design guidelines for specific applications).
- *Design for Advanced Manufacturing Technologies and Processes*, LaRoux K. Gillespie, Society of Manufacturing Engineers, McGraw-Hill, 2017 (includes thousands of design guidelines for advanced manufacturing processes and materials).
- *Product Design for Manufacture and Assembly, Third Edition,* Geoffrey Boothroyd, Peter Dewhurst, Winston A. Knight, CRC Press, 2010.
- MIL-HDBK-727, Design Guidance for Producibility, 1984, includes useful design guidelines. Note: Although a source of producibility design guidelines some design and materials information contained in this military handbook may not be current with advanced materials and manufacturing processes.
- MIL-HDBK-338B, Electronic Reliability Design Guidebook.
- MIL-HDBK-454B, General Guidelines for Electronic Equipment.

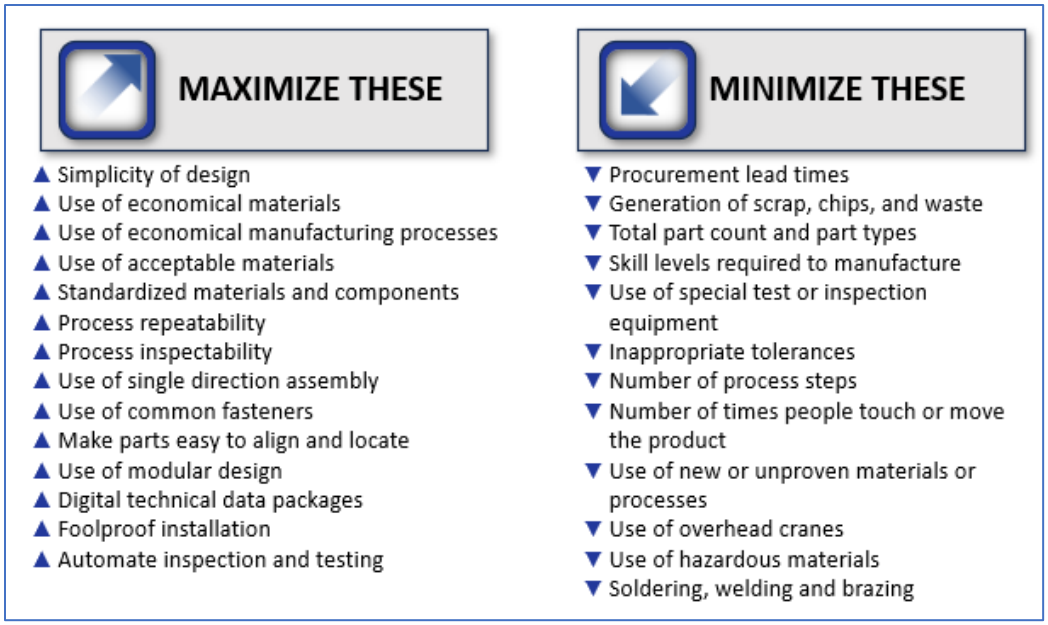
6.3.2 Design for Manufacture and Assembly

Design for manufacture and assembly (DFMA) (Boothroyd et al. 2010) is a design approach to ensure the design can be manufactured and assembled easily to meet specification and quality requirements. A few simple examples are to design components to include self-aligning parts, use of standard tools, or error proofing of the assembly process so parts can be assembled only one way and cannot be incorrectly assembled. More complex design analysis may be required to engineer components with wider tolerances that perform as well as designs with tighter tolerances, or use of easier-to-machine materials versus exotic alloys or hardened metals.

Stakeholders (design, manufacturing, quality, tooling, materials, suppliers, etc.) in an IPT environment need to assess the design and challenge the designers to enhance producibility and remove unnecessary costs. DFMA examples include:

- Process: Choose the correct manufacturing processes, ones that are not highly capitalized. Determine the cost of fabrication of individual parts, components, and products. As a best practice, the IPT should consider production rate and quantity since these factors play a significant role in determining costs.
- Design: Must conform to good manufacturing practices that are well established, with known outcomes. Reduce machined component features to control production costs, increase quality, and improve DFMA outcomes.
    - Reduce the number of required product parts, thereby making assembly more efficient.

  - Build fasteners into part design.
  - Mistake-proof or error proof the design so it is impossible to install parts incorrectly (often referred to as Poka-Yoke in Lean manufacturing descriptions).
  - Increase the ease of assembly by using keyed parts or components that can go together only in a certain orientation.
  - Promote ease of handling during assembly by measuring part size, weight, and ease of dispensing, fragility, and flexibility.
  - Pay attention to symmetry so that parts are easy to orient during the assembly process.
  - Where possible, orient electronic components with pin 1 or polarity in the same direction to make the component or assembly inspection easier.
  - Avoid designing left-handed or right-handed parts.
  - Consider modular design.
  - Keep tolerances realistic.
- Material: Select materials that have the appropriate properties, then choose the one that is the least costly and still provides the performance required.
- Environment: Understand the operating environment and design to that environment.
- Compliance and Testing: Ensure that the product design can meet all quality and safety requirements. The objective is to minimize design approaches that negatively impact producibility while actively taking steps to enhance ease of manufacture as indicated in Figure 6-3.



Source: Derived from DAU course materials.

Figure 6-3. Example Producibility Detailed Design Engineering Objectives

6.3.3 Producibility Analysis and Assessments

Producibility analysis examines decisions made during design, development, and material selection. It includes major functions such as system design; cost estimating and scheduling; industrial engineering; fabrication and assembly; installation and checkout; demonstration and testing; and quality assurance. (See Data Item Descriptions DI-MGT-81889B Manufacturing Plan and DI-MGMT-80797A Producibility Analysis Report.)

Producibility analysis helps to determine manufacturing requirements for the product. These derived design requirements and considerations should be added to the requirements before the PDR and CDR. Example producibility analysis tools are included in Table 6-6.

Table 6-6. Example Producibility Analysis Tools

Title	Brief Description
Fishbone Diagram (Ishikawa Analysis)	A method to brainstorm causes of why the design is not producible. Analysts rank which are most likely or severe to include requirements, design documentation, process flow, potential failure modes (understanding why the design is not producible).
Failure Modes and Effects Analysis (FMEA)	A method to identify failures, including failures in producibility, and to develop mitigations to ensure producible design. These mitigations become design requirements. Supports identification of potential design failure modes that would result in a design that is not optimized for producibility.
Quality Function Deployment	A way to decompose technical and system requirements to design requirements.

Title	Brief Description
Design FMEA (DFMEA)	A technique used to analyze, prior to entering the manufacturing phase of development, a part's design to identify potential failures, errors, and defects and their effect on cost and risk. Evaluation of the DFMEA are inputs to identification of Key Characteristics and Critical Characteristics in the PFMEA.
Process FMEA	A failure modes and effects analysis approach focusing on potential manufacturing or manufacturing assembly processes that may result in manufacturing-related defects, scrap, rework, or system performance failures.
Producibility Assessment Worksheet (PAW)	A producibility data collection approach to summarize expert opinions on specific producibility topics. The PAW provides input to the IPT on potential producibility issues and to help the design team develop courses of action for resolution.
Pugh Matrix Analysis	Concept selection and comparison matrix. The objective is to compare concepts to down-select the best option. By using this tool, engineers can look at different producibility concepts and qualitatively compare how the design would meet technical requirements.
Error Proof the Design	Focuses on eliminating or reducing the possibility of error during the manufacturing process. Examples include designing a product and process so a product can be assembled only in the correct way, use of self-aligning parts, or modular components.

A producibility assessment is a systems engineering tool used to address design and manufacturing risks early in the design process. To assess producibility on a product level, both the product and its manufacturing processes should be assessed. As follow-up to this assessment, manufacturing processes should be monitored and controlled, through measurement, to ensure they can repeatedly produce accurate, high-quality products, which helps the program meet objectives for limiting process variability to a tolerable range.

One assessment approach is to quantify the projected degree of producibility of the various candidate fabrication processes by assigning numerical values for each process element, which, when averaged, indicate a measure of the probability of successful production. This producibility index is calculated using a Producibility Assessment Worksheet (PAW). It is predicated on subjective data, or information based on the evaluator's experience with similar products. The worksheet is beneficial in a product's early development because it is designed to communicate an evaluator's knowledge, experience, and expert judgment. The worksheet also accounts for what the evaluator knows about the product's design as well as what resources may be used in production. This information can then be shared between members of the engineering and management teams to communicate the prospects for success. The worksheets represent a useful tool to initiate and maintain communication between functional organizations. A description of the PAW process with sample worksheets is included at Appendix B.

Key Reference

- NAVSO P-3687, Producibility Systems Guidelines.

6.3.4 Key Characteristics and Critical Characteristics

As a best practice in producibility engineering, the program should identify Key Characteristics (KCs) and Critical Characteristics (CCs) during the design process and specify them in technical data packages and manufacturing work instructions. The program should closely monitor and control the KCs and CCs through analysis techniques such as the Taguchi Loss Function to aid in the development of robust designs. The following definitions are provided for KCs and CCs:

KC: “The feature of a material or part whose variation has a significant influence on product fit, performance, service life, or manufacturability.” (MIL-HDBK-896A, page 19).

CC: “… 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.” (DOD-STD-2101, page 19).

Key References

- ISO 9001, Quality Management System.
- SAE AS9100, Quality Management Systems.
- SAE AS9103, Quality Management Systems –Variation Management of Key Characteristics.
- SAE AS6500A, Manufacturing Management Program.
- DOD-STD-2101, DoD Standard Practice: Classification of Characteristics.
- MIL-HDBK-896, Manufacturing Management Program Guide.

6.3.5 Critical Manufacturing Processes

A critical manufacturing processes is a manufacturing process that has been evaluated and approved for use in the production of an item, where the item's critical nature demands strict control of its manufacture; or in cases where a specific manufacturing process is required for successful production or performance of the item. As a best practice, M&Q specialists should require the contractor to identify potential critical manufacturing processes and address them in the producibility plan.

Key References

- DI-SESS-81012, Proposed Critical Manufacturing Processes.
- DI-SDMP-81476A, DoD Manufacturing Process Standards Documents.

6.3.6 Tolerance Design

Tolerance is the total amount of variation a dimension can have and still be considered acceptable. It is the difference between the specification's upper limit (maximum) and lower limit (minimum). Variation exists in all processes and products, so tolerances are developed and used on production drawings to control the parts or to limit the variability allowed on parts to an acceptable level.

A primary concern during the design process is to determine how wide the tolerances can be without affecting other factors or the outcome of the process. Engineering experiments include, for example, Design of Experiments (DOE), Taguchi methods, and Monte Carlo simulations.

Tolerances are particularly important when mating parts in an assembly. Tolerances should be established or determined during the design phase to ensure that parts, components, and sub-assemblies can be assembled easily and after assembly can perform their function(s) with minimal adjustment. Tolerancing should be appropriate to the requirements. Too tight a tolerance may drive up costs and defect rates. Too loose a tolerance may result in poor performance or poor reliability. One of the great advantages of using appropriate tolerances is that it allows for interchangeable parts, thus permitting the replacement of individual parts.

Tolerancing is most important when dealing with KCs or CCs; thus, it is important to accomplish tolerance analysis as a part of tolerance design. Tolerancing influences the cost and performance of products. Tolerance analysis is a way of understanding how sources of variation in part dimensions and assembly constraints propagate across parts and assemblies and how that total variation affects the capability of a design to achieve its design requirements within the process capabilities of manufacturing organizations and supply chains.

6.3.7 Tolerance Stacking

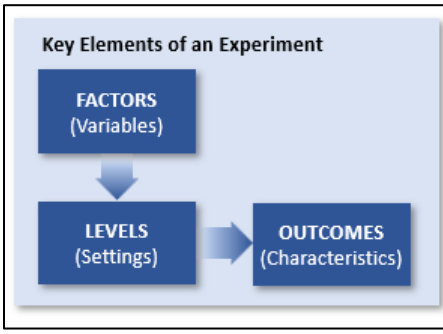
Tolerance accumulation between surfaces, or "tolerance stacking" analysis, is defined in American Society of Mechanical Engineers (ASME) Y14.5, Dimensioning and Tolerancing. Tolerance analysis would typically consider tolerance stacking by use of experimental analysis, worst case, or statistical analysis tools. How a drawing is dimensioned (e.g., chain dimensioning, base line dimensioning or direction dimensioning) affects tolerance accumulation, with chain dimensioning resulting in the greatest tolerance accumulation and direct dimensioning resulting in the least tolerance accumulation.

6.3.8 Taguchi Robust Design

Taguchi robust design is a statistical method to produce a high-quality product and optimize the process design in a cost-efficient way by reducing variation through robust DOE. As such, robust/parameter designs help support producibility efforts by identifying and reducing variation

in a product, allowing the product to perform its functions regardless of the causes of variation (noise factors).

An experimental design is used to identify and exploit the interactions between control and noise factors. Once the significant factors have been identified and their control settings established, the resultant product will be optimized by designing quality into the product and processes. Traditional DOE using orthogonal array vary only one factor at a time, thus creating many experiments. This approach is expensive and time consuming. Taguchi's approach to DOE reduces the number of experiments. Figure 6-4 provides an example experiment summary using variables, settings, and outcomes.



Factors	Level	Total Experiments (Factorial Design)	Total Experiments Taguchi Design
2	2	4	4
3	2	8	4
4	2	16	8
7	2	128	8
15	2	32,768	16

Figure 6-4. Example Experiment

The Taguchi method involves the following steps:

1. Select the appropriate controls, response, and noise factors for experimentation.
    a. Controllable input factors and parameters.
    b. Measurable output or response (performance).
2. Define the experiments' objective or function to be optimized.
    a. Optimize or maximize the output or performance.
    b. Minimize variations in output or response.
3. Plan for experimentation to identify and elicit a desired response.
    a. Full or factorial designs can identify interactions.
    b. Orthogonal arrays can identify main effects using fewer experiments.
4. Conduct the experiment by varying the input and noise factors.
    a. Record the results of the experiment.
    b. Compute the objective function.
5. Conduct an analysis of means to identify which parameters impact output the most.
6. Manage the output to optimize the output by setting control set points.
7. Conduct confirming experiments.

Key References

- Training: DAU PQM 301 Lesson 21 Design of Experiments.
- "What Are Taguchi Designs?" (NIST Handbook 5.5.6).

6.3.9 Taguchi Loss Function

Taguchi Loss Function is a graphical technique to show how an increase in variation from the target value on a KC or CC can have an exponential impact on cost, reliability, and customer satisfaction.

As shown in Figure 6-5, the specification limit and target value for the product on the left has a low loss function, that is, there is little cost from moving away from the target value. Also, of the two data points on the left graphic, one is "in specification," while the other is "out of specification." For many specifications, even when outside of the upper and lower control limits, there is a low loss. Because there is low loss, the engineering solution to this type of product defect is "use as is." Thus, this specification is not a KC.

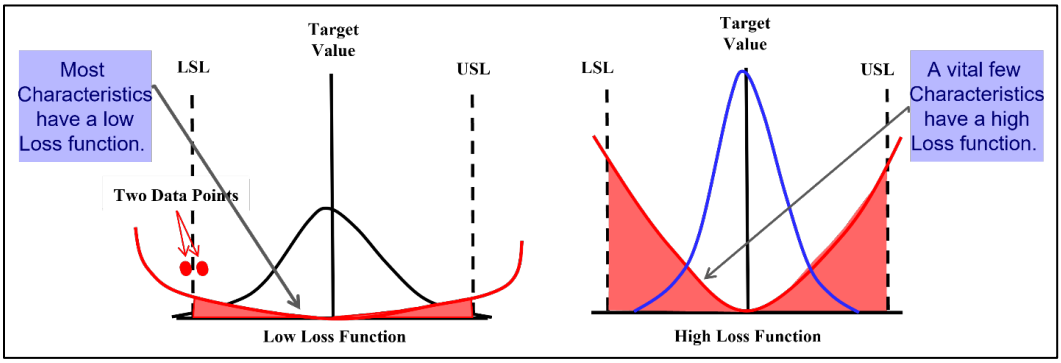


Figure 6-5. Example Loss Functions

The specification limit and target value for the product on the right has a high loss function. That is, significant cost is incurred as the manufacturer moves away from the target value. Note that there is a high loss even within the specification limits. This specification is considered a KC and must be managed and controlled. A KC has the greatest impact on form, fit, function, and performance compared with all other non-KCs and CCs.

The loss function should be a part of Parameter Design, which refers to identifying control factors for the process to determine the optimal (target) level of each factor. Initially in this method, design is developed using low-cost parts and manufacturing methods. Afterward, the response is optimized to minimize noise. The goal of this method is to find the efficient process (functionality robust) and service design.

This process also leads to tolerance design, which identifies the acceptable limit of deviation in a parameter's dimension or value, which must be determined for all system components. In other

words, Tolerance design maintains the balance between quality and design cost. Thus, Tolerance design creates metrics allowing the designer to compute the tolerances that can be adjusted to meet customer needs and expectations while delivering a cost-effective product.

6.3.10 Process Design Impact on Producibility

As part of concurrent engineering approaches, in addition to detailed product design, process design is the complete identification and description of specific steps in the production process and the flow of those steps that will result in a final product. Process design can be used by organizations to optimize production operations when producing a product that is dependent on processes to control the output. Typically manufacturing operations follow one of several production flows:

- Repetitive (or assembly line): Production of the same or similar product with little setup or changeover. Production rate can be adjusted based on demand.
- Discrete: Similar to repetitive, but there are frequent setups and changeovers.
- Project (e.g., one of a kind, custom).
- Job shop: Various production areas within a facility focus on one product in smaller batches.
- Batch processing: Production based on customer demand; provides similar products but may require diverse production processes based on each customer's product requirements.
- Continuous flow: Manufacturing process for raw materials such as oil refining, metal smelting, liquids, and gases, etc.

Process designers should consider the following factors:

- Product variety (i.e., high volume/low mix or low volume/high mix).
- Required production rates and quantities.
- Required manufacturing technology.
- Skill level of employees.
- Length of production program.

When a product is designed, manufacturing and industrial engineers should be involved to influence the design for producibility and to initiate manufacturing process planning. The product needs to be analyzed to determine what parts and components are needed, to identify production operations, to determine task sequencing, and to understand process capability.

Program requirements also should be considered in conjunction with specific parts and product requirements, as they may drive considerations that must be accounted for during process planning activities. Examples include program security, system safety, and hazardous materials such as explosives and chemicals production.

Process planning also includes identifying key and critical manufacturing processes and product flow for both fabrication and assembly and identifying key and critical process parameters.

Process planning steps include the following:

- Analysis of part and program requirements.
- Selection of raw materials.
- Determining manufacturing operations and their sequences.
- Selection of machine tools.
- Selection of tools, jigs, fixtures, and inspection equipment.
- Determining machine conditions (cutting speed, feed, and depth of cut).
- Factory floor layout.
- Work instructions.
- Manufacturing times (setup time, lead time, and processing time).

Process control uses the earlier identification of key and critical product and process characteristics to establish process parameters and then to control processes using statistical techniques.

During process design, the design team, with input from M&Q specialists, industrial engineers, and process engineers, should conduct a PFMEA to identify and mitigate potential manufacturing or manufacturing assembly processes that may result in manufacturing-related defects, scrap, rework, or system performance failures. SAE Standard J1739, Potential Failure Modes and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA is the industry standard for performing the PFMEA.

Manufacturing Work Instructions

Manufacturing work instructions are essential to specify processes for production, inspection, and test of any article. The general format and approach of work instructions are typically specific to the company making the product, but they tend to reflect industry-specific standards, such as International Organization for Standardization (ISO) 9001. As a best practice, work instructions should be under document control to ensure the latest approved instructions are being used. Manufacturing work instructions must address many details, but their main purposes can be categorized as follows:

- Communicating safety and skills training to workers.
- Process and system flow: how each production step connects to the next.
- Implementing standardized quality control.

Effective work instructions incorporate Lean principles such as continuous improvement and eliminating waste from cycles, which act as a means of creating a quality product with the fewest possible defects and the least material waste. Examples:

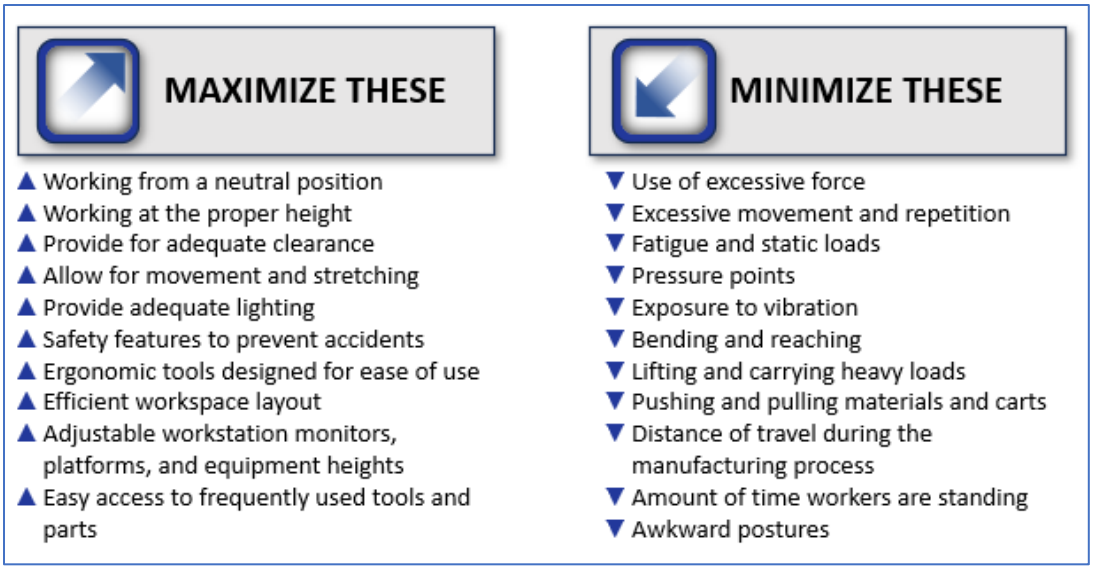
- Routings, specify operations, operation sequences, work centers, standards, tooling, and fixtures. This routing becomes a major input to the manufacturing resource planning system to define operations for production activity control purposes and defines required resources for capacity requirements planning purposes.
- Process plans, which typically provide more detailed, step-by-step work instructions including dimensions related to individual operations, machining parameters, setup instructions, and quality assurance checkpoints.
- Fabrication and assembly drawings to support manufacture (as opposed to engineering drawings to define the part).

Industry 4.0 technologies enable more effective work instructions. For example, the incorporation of artificial intelligence allows work instruction to adapt to changing conditions on the production floor. In addition, virtual and augmented reality can provide workers with heads-up displays of work instructions, which can be augmented with other graphical and support information.

6.3.11 Design for Ergonomics

Design for ergonomics (DFE) focuses on the design of equipment, tools, jobs, and other workplace processes that may be useful in improving the overall level of physical comfort experienced by employees in relation to their working environment and, by doing so, may improve individual and collective efficiency and productivity. Ergonomic designs take into consideration human factors (size, weight, height, reach, etc.) when designing products and manufacturing processes that will be used to make those products so that the impact to the human is minimized. Good ergonomics help reduce the stress of repetitive movements.

The IPT may require input from industrial engineers, process engineers, human factors, safety subject matter experts, or ergonomic engineers. The principles of ergonomic designs should include the design of a product that allows workers to manufacture the product quickly, easily, and safely with high quality and low cost. Example DFE objectives are included in Figure 6-6.



Source: Derived from DAU course materials.

Figure 6-6. Example DFE Objectives

Key Reference

- DI-SDMP-81476A, DoD Manufacturing Process Standards Documents.

6.3.12 Design for Test

Design for Test (or Testability) (DAT) includes adding testability features in the product design to facilitate testing during manufacture and inspection. Other considerations are test inspection capabilities on the factory floor. Having available workforce skills, test equipment, and special test equipment in-house can impact yields, quality escapes, production rates, cost, and ability to deliver products.

Key References

- IEEE 1149.1 (2013), Standard for Test Access Port and Boundary-Scan Architecture.
- IEEE 1149.1, (JTAG) Testability Primer.
- MIL-STD-1916, Department of Defense Test Methods Standards: DoD Preferred Methods for Acceptance of Products (1996), Notice 2 (2014).
- MIL-A-70625A, Military Specification, Automated Acceptance Inspection Equipment Design, Testing and Approval, and Notice 2 (April 2000).

6.4 Systems Engineering Technical Reviews Supporting Detailed Design

6.4.1 Preliminary Design Review

The intended outcome of the PDR is to deliver the confidence to move forward with a detailed design. The PDR determines whether the preliminary design and basic system architecture are complete. It ascertains whether the capability requirements can be met within cost and schedule goals. The PDR also identifies risks and establishes mitigation plans. More important, the PDR serves as a forum for all the stakeholders to understand the trade studies conducted during the preliminary design, providing insight into the thought processes behind the design decisions that are consistent with the user's performance, schedule needs, and applicable requirements documents. A successful PDR serves as confirmation that the system's preliminary design:

- Satisfies the requirements documented in the system performance specification.
- Is affordable, testable, producible, and sustainable and carries an acceptable level of risk.
- Is composed of technologies demonstrated in a relevant environment that can be integrated into a system with acceptable levels of risk.
- Is complete and ready for detailed design.

During the PDR, suggested producibility topics for the IPT include review of:

- Trade studies and design study results to include producibility considerations.
- Recommendations and requirements for industrial modernization and capacity.
- Preliminary list of materials, parts, and processes.
- Sole source, single source, or foreign source components and materials.
- Manufacturing considerations (e.g., availability of tooling, processes, facilities, required manufacturing skills).

Example PDR producibility considerations are outlined in Table 6-7.

Table 6-7. PDR Producibility Considerations

Product	Preliminary Design Review (PDR) Considerations
Producibility Planning	• System cost model has been updated, allocated to lower system element levels, and tracked against targets; production cost model constructed. • All entrance criteria stated in the contract (e.g., SOW, SEP, approved SEMP, and system performance specification) have been satisfied. • Producibility plans have been documented in the SEP. • Preliminary design choices have been assessed for industrial base constraints. • DMSMS Management Plan is in place and being applied to mitigate DMSMS risk in preliminary designs.

Product	Preliminary Design Review (PDR) Considerations
	• Review and update supply chain management planning. • Integrating activities of any lower-level PDRs have occurred; identified issues are documented in action plans. • Manufacturing and production plan to Critical Design Review is accurately documented in the SEP as well as the IMP and IMS. • Production program is properly staffed. • Manufacturing personnel can access needed data within the digital engineering ecosystem to make informed decisions. • Adequate processes and metrics are in place for the program to succeed. • Production schedule is depicted in the updated IMS. • Production program is executable with the existing budget and the approved product baseline. • Long-lead and key supply chain elements are identified. • Long-lead procurement plans are in place; supply chain assessments are complete. • Conduct Industrial Capabilities Assessment (update required at each Milestone (10 USC 4820 (formerly 2440)).
Producibility Engineering	• Preliminary design satisfies producibility design considerations. • Producibility assessments of key technologies are completed. • Preliminary design choices have been assessed for manufacturing processes. • Producibility enhancement efforts have been initiated (i.e., DFMA, DFSS, DFE, DFT). • Design for testability and inspectability have been initiated. • Trade studies and system producibility assessments are under way. • Majority of manufacturing processes have been defined, characterized, and documented. • Potential Key Characteristics and Critical Characteristics have been identified and documented. • Identify potential critical manufacturing processes. • Identify hazardous materials. • Preliminary system-level design is producible and assessed to be within the production budget. • Conduct root cause analysis. • Initial PFMEA analyses are complete. • Initial Development Level Technical Data Package has been developed. • Review manufacturing data rights requirements and status. • Allocated baseline documentation is sufficiently complete and correct to enable detailed design to proceed with proper configuration management. • Parts lists have been evaluated for compliance with the Parts Management Plan. • Assess contractor’s manufacturing capability to produce in a production representative environment. An initial manufacturing approach has been developed. • Detailed design is producible and assessed to be within the production budget.

Product	Preliminary Design Review (PDR) Considerations
	• Detailed producibility trade studies using design characteristics and related manufacturing process are completed. Materials and tooling are available to meet the pilot line schedule. • Identify preliminary KCs and CCs for the proposed design approach(s) and potential mitigation plans. • Verify configuration control of the initial product baseline as demonstrated by the completion of build-to documentation for hardware and software configuration items, production models, drawings, software design specifications, materials lists, manufacturing processes, and qualification plans and procedures. • Use Additive Manufacturing and Digital Engineering for rapid prototyping. • Manufacturing Readiness Assessment update.
Process Capability	• Conduct projected and actual process capability studies using process performance index and process capability index. • Use SPC techniques to determine stable and variable processes.

6.4.2 Critical Design Review

The purpose of the Critical Design Review (CDR) is to confirm the system design is mature and stable – that it is expected to meet system performance requirements and cost goals. It is supposed to provide acquisition stakeholders with evidence that the system, down to the lowest system element level, is expected to meet the requirements of the system performance specification as derived from the Capability Development Document (CDD) within current cost and schedule constraints.

The product baseline initially established in the CDR describes the detailed design for production, fielding, deployment, and operations and support. The product baseline proposes all necessary physical (form, fit, and function) characteristics and selected functional characteristics designated for production acceptance testing and production test requirements. It is traceable to the system performance requirements contained in the CDD. The initial system element product baseline is established and placed under configuration control at the system element CDR and verified later at the Physical Configuration Audit (PCA).

During the CDR, suggested producibility topics for the IPT include review of:

- Status of producibility efforts and analysis.
- Efforts to resolve manufacturing issues identified in previous reviews.
- Status of manufacturing technology projects.
- Identification of KCs and CCs.
- Approach to SPC.

- Tooling, special tooling and test equipment, new materials, processes, and methods.
- Manufacturing management program and organization for production.

Example CDR producibility considerations are outlined in Table 6-8.

Table 6-8. CDR Producibility Products and Considerations

Producibility Area	Critical Design Review (CDR) Considerations
Producibility Planning	• System production cost model has been updated. • PDR producibility actions are successfully completed; all PDR producibility actions are closed. • Adequate processes and metrics are in place for the manufacturing program to succeed. • Program schedule included production and depicted in the updated IMS. • Manufacturing is properly staffed. • Detailed trade studies and system producibility assessments are under way. • Materials and tooling are available to meet the pilot line schedule. • DMSMS Management Plan is in place and being applied to mitigate DMSMS risk in critical designs. • Review and update supply chain management planning. • Long-lead procurement plans are in place; supply chain assessments are complete. • Detailed design is producible and assessed to be within the production budget. • Planning for Low-Rate Initial Production has been conducted.
Producibility Engineering	• Detailed design is complete, or projected engineering changes identified. • Requirements trace among functional, allocated, and initial product baselines is complete and consistent. • Producibility enhancement efforts ongoing (i.e., DFMA, DFSS, DFE, DFT). • Design for testability and inspectability efforts ongoing. • KCs and CCs are identified and documented. Potential KC/CC risks and mitigation plans identified. • Manufacturing processes have been reassessed for detailed design. • Identify critical manufacturing processes. • Identify hazardous materials. • Select DMSMS resilient parts. • Initial product baseline documentation or digital artifacts are sufficiently complete and correct to enable hardware fabrication. • Conduct root cause analysis. • PFMEA analyses and risk assessments are complete. • Producibility risk assessments and risk mitigation plans have been updated, documented, formally addressed, and implemented. • Final Developmental Technical Data Package has been completed. • Initial Product Level Technical Data Package has been initiated. • MRL assessments are updated and completed.

Producibility Area	Critical Design Review (CDR) Considerations
Process Capability	• Critical manufacturing processes that affect the product characteristics have been developed, process control plans have been developed and demonstrated, and the capability to meet design tolerances has been determined. • Conduct projected and actual process capability studies using process performance index and process capability index. • Use SPC techniques to determine stable and variable processes.

6.4.3 System Verification Review/Functional Configuration Audit

The System Verification Review (SVR)/Functional Configuration Audit (FCA) is the technical assessment point at which the actual system performance is verified to meet the requirements in the system performance specification and is documented in the functional baseline. The terms SVR and FCA are sometimes used synonymously when the FCA is at the system level. When a full system prototype is not being evaluated, the FCA is used to validate system element functionality. FCA is usually conducted after the EMD phase and CDR. The SVR/FCA is used to:

- Assess whether system development has been acceptably completed.
- Review documentation for completeness and adequacy.
- Confirm that the product baseline meets the requirements of the functional baseline Roles and Responsibilities.

Producibility does not play a major role in the SVR; however, manufacturing personnel should engage with the SVR team since one output will be the PM approval to proceed to the PRRs.

Example SCR/FCA producibility considerations are outlined in Table 6-9.

Table 6-9. SVR/FCA Products and Considerations

Producibility Area	System Verification Review (SVR)/Functional Configuration Audit (FCA) Considerations
Producibility Planning	• Establish the plan to the PRR in applicable contract documents, including the SEMP, IMS, and IMP. • Review the completed documentation or digital artifacts to include manufacturing work instructions. • Review FRP plans.
Producibility Engineering	• Ensure producibility risk items associated with the verified product baseline are identified and analyzed, and mitigation plans are in place. • Conduct root cause analysis. • Review PFMEA information.

6.4.4 Production Readiness Review

The Production Readiness Review (PRR) determines whether the system design is ready for production and whether the developer has accomplished adequate production planning for entering LRIP and FRP. Production readiness increases over time with incremental assessments at various points in the program life cycle. The PRR is intended to provide fact-based evidence that the system can be produced with an acceptable level of risk within cost, schedule, and performance limits. As a best practice, the PRR should include an assessment of the producibility program and activities to include considerations.

For complex systems, a PRR may be conducted for one or more system elements. In addition, periodic production readiness assessments to include MRL assessments should be conducted during the EMD phase to identify and mitigate risks as the design progresses. The incremental reviews lead to an overall system PRR. Example PRR producibility considerations are outlined in Table 6-10.

Table 6-10. PRR Considerations

Producibility Area	PRR Considerations
Producibility Planning	• Prior readiness reviews are completed, and action items closed. • Review and update supply chain management planning. • Supply chain is stable and adequate to support planned LRIP and FRP. • Program is properly staffed with qualified production, quality (engineering and assurance) and manufacturing personnel. • Product acceptance system, including acceptance test procedures and associated equipment, has been validated and put under configuration control. • LRIP and FRP planning is complete. • Final Product Level Technical Data Package have been completed. • Failure Reporting Analysis and Corrective Action System (FRACAS) is in place to track defects and failures during production. • Production facilities are ready and required personnel are trained. • Delivery schedule is executable (technical/cost risks, long lead items.) • DMSMS management plan is in place; DMSMS mitigation ongoing. • Assess contractor's manufacturing capability to produce on a production-representative line (LRIP). • The detailed system design is complete and stable to support LRIP. • Technologies are mature and proven in a production environment, and manufacturing and quality processes are capable, in control, and ready for LRIP. • All materials, manpower, tooling, test equipment, and facilities have been proven on pilot lines and are available to meet the planned LRIP schedule. • Cost and yield and rate analyses are updated with pilot line results. • Known producibility risks pose no significant challenges for LRIP.

Producibility Area	PRR Considerations
	• Supplier qualification testing complete and Engineering and Manufacturing Development (EMD) builds validated against Technical Data Package (TDP) requirements. • Industrial base capabilities assessment for Milestone C has been completed and shows that the supply chain is adequate to support LRIP. • Conduct Industrial Capabilities Assessment (Update required at each Milestone per 10 USC 4820 (formerly 2440)).
Producibility Engineering	• Producibility trade studies and risk assessments are completed. • Product baseline is stable and under proper configuration control to enable hardware fabrication in low-rate production. • Manufacturing technologies are mature and proven. • Design is ready for production. • Key and critical manufacturing process are under SPC. • PFMEA monitoring, corrective action plans are documented. • Manufacturing processes are stable and have been demonstrated in a pilot line environment. • Adequate production line processes and metrics are in place for the delivery of on-time, quality products. • Manufacturing production risks, including DMSMS, are identified and mitigation plans are in-place. • Cybersecurity vulnerabilities, threats, and risks are known and mitigated (see MRL Operational Technology Cyber security assessment criteria) • Update Manufacturing Readiness Level assessment.
Process Capability	• Critical manufacturing processes that affect the product characteristics have been demonstrated, and the capability to meet design tolerances has been validated. • Process control plans are in place for critical manufacturing processes to include SPC.

6.4.5 Physical Configuration Audit

The Physical Configuration Audit (PCA) is a formal examination of the "as-built" configuration of the system or a configuration item against its technical documentation to establish or verify its product baseline. At the conclusion of the PCA, the final product baseline is established, and all subsequent changes are processed by formal engineering change action.

The PCA confirms these producibility-related considerations:

- The product baseline has been updated to include current design documentation.
- Production-related activities are focused on a validated and accurate design.
- The manufacturing processes, quality control system, measurement and test equipment, and training are adequately planned, tracked, and controlled.

The PCA is also used to verify that any elements of the configuration item that were redesigned after the completion of FCA also meet the requirements of the configuration item's performance specification.

Example PCA producibility considerations are outlined in Table 6-11.

Table 6-11. PCA Producibility Considerations

Producibility Area	Physical Configuration Audit (PCA) Considerations
Producibility Planning	• Assessment that the product baseline is complete and accurately reflects the configuration is production representative.
Producibility Engineering	• Prior producibility improvements analyzed for effectiveness during LRIP. • Producibility and manufacturing risks are identified and documented at levels low enough to continue with FRP and deployment.
Process Capability	• Confirm GD&T are within specification. • Manufacturing engineering should verify KCs and CCs in the final production product.

Key References

- MIL-HDBK-61B, Configuration Management Guidebook.
- DoD Systems Engineering Guidebook.
- Early Manufacturing and Quality Engineering Guide.
- DoD Systems Engineering Plan Outline, Version 4.1.
- DoD M&Q Body of Knowledge.
- DoDI 5000.84, Analysis of Alternatives.
- IEEE-15288.2, Standard for Technical Reviews and Audits on Defense Programs.
- MIL-HDBK-896, Manufacturing Management Program Guide.

7 PRODUCIBILITY: PROCESS CAPABILITY

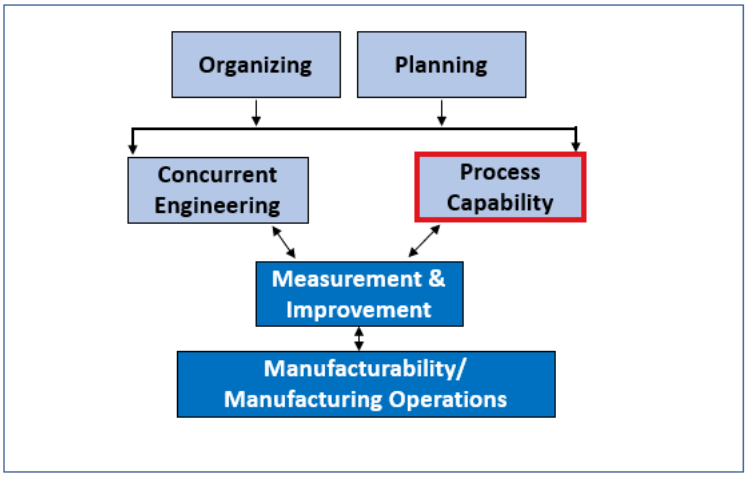


Figure 7-1. Major Producibility Activities—Process Capability

One of the major goals of manufacturing is to provide the customer with uniform, defect-free product that provides consistent performance and is affordable. Product quality comes from robust product and process design and control activities including continuous improvement to identify and remove sources of variation. This section discusses the process capability activities highlighted in red (bold outline) in Figure 7-1. These activities foster mature processes with high capability indices.

To assess producibility on a product level, both the product and its manufacturing processes should be assessed. Manufacturing processes should be monitored and controlled, through measurement, to reduce variability and to ensure they can repeatedly produce accurate, high-quality products.

7.1 Variation and Variability Reduction

Variation may be defined as any unwanted condition or as the difference between a current and a desired end-state. Both product performance and manufacturing processes exhibit variation.

M&Q specialists should be aware of the origins of variation in a process. Two categories are used across industry: common causes and special causes. Common causes of variation are inherent in the process and affect every outcome and are usual, historical, quantifiable, and predictable. Special causes of variation arise because of specific circumstances and are typically unusual, non-quantifiable, not previously observed, or unpredictable.

To manage and reduce variation, the variation must be traced to its root cause. There are four primary sources of variation:

- Inherent variability of manufacturing processes from factors such as manpower, materials, work methods, machinery, and measurement.
- Inherent measurement systems variability, even if properly calibrated.
- Variability of components to include parts from subcontractors and physical interfaces.
- Insufficient design margins resulting from design practice, unrealistic requirements, and changing requirements.

A primary objective of producibility is to reduce and control variation in the manufacturing process. Variation reduction measures include:

- Stable, realistic requirements.
- Design process that includes producibility as a major consideration.
- Use of proven, mature manufacturing processes.
- Use of process control tools such as Design of Experiments, SPC, and Analysis of Variance on the manufacturing shop floor (Motley n.d., DAU).

Central to producibility is process capability and control to measure and control variation during the manufacturing process. A process capability index uses both the variability and the process specifications to determine whether the process is "capable." Process capability compares the output of an "in-control process" to the specification measured by six standard deviations. Additional process and product monitoring information and tools are available from NIST.

7.2 Process Capability Studies and Control Process Capability Studies

The NIST Engineering Statistics Handbook (section 6.1.6) provides a detailed description of process capability and indices. In summary, NIST states,

> Process Capability compares the output of an in-control process to the specification limits by using capability indices. The comparison is made by forming the ratio of the spread between the process specifications (the specification "width") to the spread of the process values, as measured by 6 process standard deviation units (the process "width").

Process capability studies help ensure a manufacturing process produces uniform, defect-free product. To be considered uniform and defect free, parts being produced must meet the engineering specification requirements and fall between the upper and lower specification limits (USL and LSL) as depicted in Figure 7-2. Process capability looks at product to see if manufacturing is producing "good parts" and can be used to predict future behavior.

The production process should be:

- Centered about the target or nominal value as defined by the design engineer.
- Within the upper and lower specification limits.
- Classified as a capable or not capable process.
- Producing good parts or with some non-conformances.

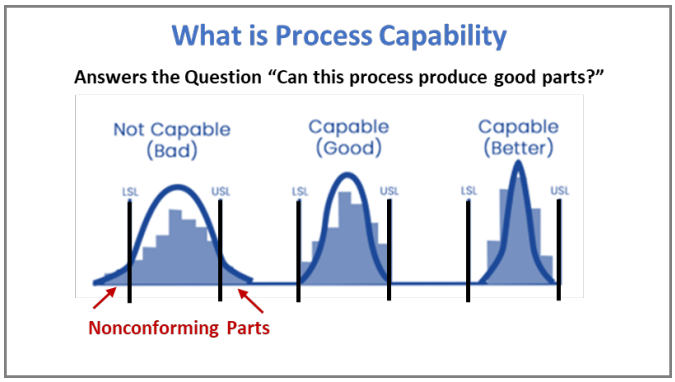


Figure 7-2. Process Capability

Process capability (Cp and Cpk) studies measure the extent of variation a process experiences relative to its specification limits. As depicted in Figure 7-3, process capability includes two indices:

- Cp – Process Capability, a measure that assumes the process mean is centered between the upper and lower specification limits.
- Cpk – Process Capability Index, a measure of actual capability during production. Assumes the center of the process shifts over time (is not centered on the target value).

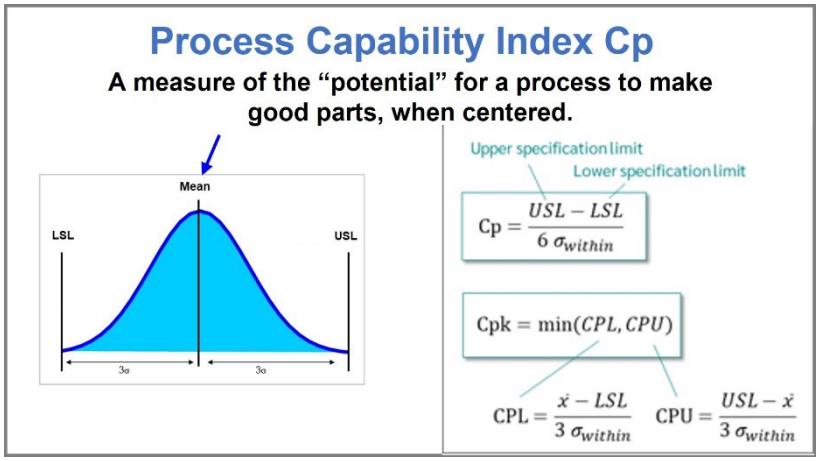


Figure 7-3. Process Capability Index

Cpk estimates the potential of a process to meet specifications in the short term—typically when there is not enough historical data (e.g., limited production quantities and rates). The population is small, and production is only for a short period, thus the study is a short-term study and cannot be used to predict future process output. An organization might use Cp and Cpk when initially setting up a new process.

Figure 7-4 shows how processes can shift over time, causing problems on either the upper or lower control limits, sometimes on both. Processes need to be managed and controlled so that only conforming product is produced and variation in processes is continuously reduced so that in the future "only conforming product" will be produced.

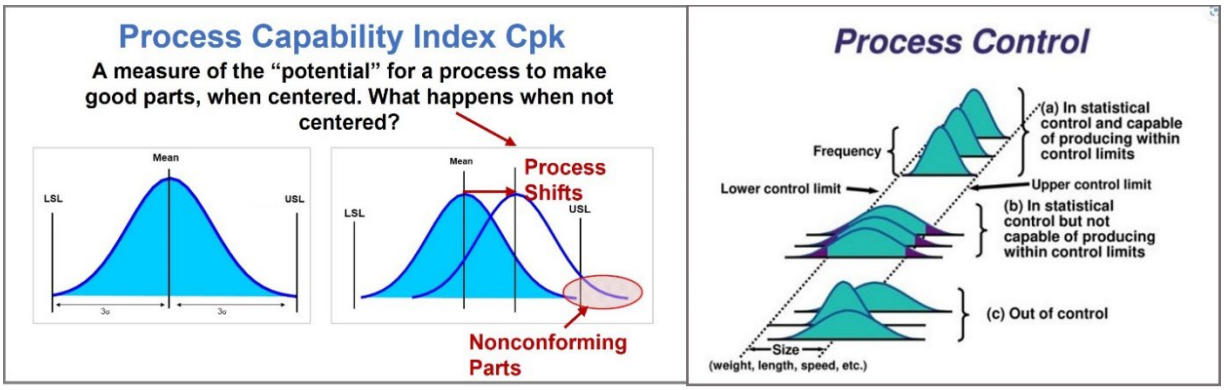


Figure 7-4. Process Capability Index and Process Control

7.3 Process Performance Studies

Although similar to Cp and Cpk studies, process performance studies (Pp and Ppk) assess actual performance over the long term. Figure 7-5 provides a summary.

	Short-Term Performance	Long-Term Performance
Considers Centering	**Cpk**	**Ppk**
Does Not Consider Centering	**Cp**	**Pp**

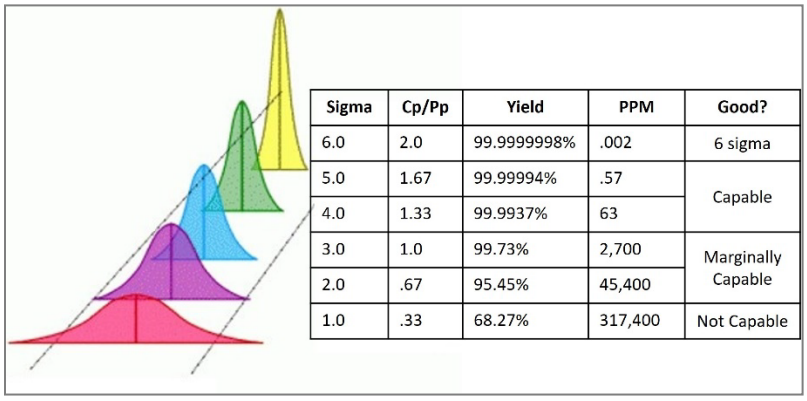
Figure 7-5. Capability and Performance Studies Comparison

Pp and Ppk studies have a lot in common with Cp and Cpk, but Pp and Ppk studies apply to processes that are stable, in statistical control, and in production, or they are used to assess the entire process. The process must be in a steady state (equilibrium) to calculate its standard deviation. The NIST Engineering Statistics Handbook states, "Most capability indices estimates are valid only if the sample size is 'large enough.' Large enough is generally thought to be about 50 independent data values." Pp and Ppk estimates assume that the population forms a normal distribution and are in statistical control; only "common causes" of variation should be present. By comparison, Cp and Cpk studies can use sample data to predict the ability of the process to produce good parts according to the specification, allowing the process to be classified as capable or not capable of producing good parts or with acceptable non-conformances.

Process performance includes two indices:

- Pp – Process Performance, a measure of actual performance. Compares the amount of variation with the specification limits. If variation is within the specification range, the product is good.
- Ppk – Process Performance Index, a measure of actual performance but with an adjustment of Pp. Considers the effect of non-centered distributions.

As depicted in Figure 7-6, Process Performance Indicators are used to look at how the total variation from the process compares with the specification. Even special causes are included in the determination of total variation. The goal is to produce good product, so identifying problems and reducing variation to the point where defects are virtually nonexistent can support this goal.



Sigma	Cp/Pp	Yield	PPM	Good?
6.0	2.0	99.9999998%	.002	6 sigma
5.0	1.67	99.99994%	.57	Capable
4.0	1.33	99.9937%	63	
3.0	1.0	99.73%	2,700	Marginally Capable
2.0	.67	95.45%	45,400	
1.0	.33	68.27%	317,400	Not Capable

PPM: Parts per million

Figure 7-6. Interpreting Process Capability and Process Performance Indices

If the process is not providing uniform, defect-free product, then action must be taken to achieve the following to improve quality:

- Eliminate special causes of variation.
- Improve the consistency of measurement systems.
- Accomplish root cause corrective action.
- Control the process using SPC or other techniques.
- Reduce waste.

As a best practice, once improvements have been implemented, the adequacy of previous life-of-need buys of obsolete components should be assessed. The waste caused by too high process variability could invalidate assumptions used to calculate life-of-need quantities and consequently lead to the re-occurrence of a DMSMS issue.

Key References

- NIST Engineering Statistics Handbook, Section 6.

8 MANUFACTURABILITY: MEASUREMENT AND IMPROVEMENT

Manufacturability is a factory floor accomplishment to improve efficiency in manufacturing operations with efforts such as Lean techniques, theory of constraints, production parts approval process, and advanced product quality planning. Although this guide makes a distinction between producibility and manufacturability so the activities can be described in an organized manner, the concepts are closely related and have some interrelated and sometimes overlapping activities such as early planning, materials considerations, and developing efficient processes.

Achieving ease of manufacture begins with the producibility design considerations described under producibility planning and engineering activities and continues through the system life cycle. Central to manufacturing operations are measurement and improvement of manufacturing processes. This section discusses the manufacturability-related activities highlighted in red (bold outline) in Figure 8-1.

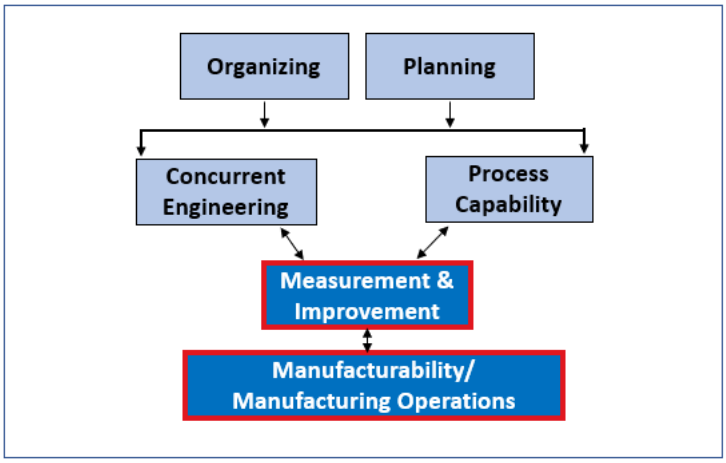


Figure 8-1. Major Manufacturability Activities—Process Measurement and Improvement

During all life cycle phases, manufacturability should be measured and improved. For example, during Production and Deployment when manufacturing operations are occurring, manufacturing engineers should implement SPC methodologies for key and critical manufacturing processes. SPC includes regular data collection intended to keep the process in a "state of control." In addition, manufacturing engineers should be aware that all measurement data also contains variation, which is the difference between the actual and observed values. To understand and mitigate sources of variation, manufacturing engineers should conduct experiments and perform analysis. They should actively manage equipment calibration and conduct measurement system analysis. As part of manufacturability efforts, M&Q practitioners should be familiar with the following:

Statistical Process Control (SPC): The American Society for Quality (ASQ) defines SPC as "…the application of statistical techniques to control a process…" This activity includes establishing and measuring the process using tools such as run charts, control charts, continuous

process improvement, and the design of experiments for early detection and prevention of problems in the production process.

Design of Experiments (DOE): The NIST Engineering and Statistics Handbook ("NIST Handbook") paragraph 5.1.1 states "the (statistical) design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions."

DOE involves the use of planned experiments to describe and explain variation in a process or product under different conditions. These methods use independent, dependent, and control variables under selected conditions to predict and measure the change in one or more of the output variables based on one or more input variables. DOE involves specifically designed experiments often performed sequentially and tailored for the unique process to maximize information gathered while efficiently minimizing testing. Commercially available software and computer programs can be used to assist in planning and analysis of DOE. In addition, to many commercial sources, NIST and ASQ provide detailed information on DOE techniques.

Calibration: Accurate calibration facilitates accuracy of measurement equipment and reduction in variation in the manufacturing process and measurement. Accurate calibration establishes and maintains:

- Acceptable performance of measurement and test equipment.
- Suitability of calibration for the intended purpose.
- Compatibility with national measurement system standards.
- Traceability of measurement results to national and international standards such as: NIST, American National Standards Institute (ANSI), NCLS International (formerly National Conference of Standards Laboratory), and International Electrotechnical Commission (IEC).

To establish the technical requirements for calibration of measurement and test equipment, manufacturing engineers should refer to calibration system requirements in standards.

Key References

- ISO 1101:2004, Geometrical Product Specifications, Geometric Tolerancing.
- ISO 10012:2003, Measurement Management Systems: Requirements for Measuring Processes and Measuring Equipment.
- ISO 9001:2015 Quality Management Systems Requirements.

Measurement System Analysis (MSA): In addition to variation in manufacturing processes and the resulting parts themselves, the process of inspection, measurements, and test data may also

have sources of variation. MSA evaluates measurement instruments, inspection equipment, and test methods to understand the integrity of the inspection and quality data and the uncertainty and error resulting from the measurement system. MSA evaluates features such as stability, linearity, and bias testing. MSA tools such as DOE, Gage R&R, Analysis of Variance (ANOVA), SPC, and FMEA assess the measurement process and characterizes its uncertainty and variability. MSA may assess causes of variation of repeated measurements as well as between similar gages, between operators, under different usage environments, and changes over time. MSA may allow for understanding of the measurement variation relative to that of the associated parts or processes.

The DOE and FMEA techniques can be used to complement MSA, but MSA is the umbrella term for all tests and evaluations used to evaluate inspection equipment. For example, an FMEA can be used to brainstorm and identify potential sources of variation in a Gage R&R study to be included as test factors, but FMEA alone is not part of MSA. Similarly, DOE can be used to design an MSA experiment but is not actually an MSA on its own. Finally, SPC is a technique to control process variation, not Gage variation; however, SPC techniques such as control charting can be used to look at gage stability, and engineers can use the information from SPC to uncouple process and measurement variation.

Key References

- ASTM International E2782, Standard Guide for Measurement Systems Analysis.
- Automotive Industry Action Group (AIAG), Measurement Systems Analysis Reference Manual, 4th Edition.
- ASME B89.7.3.1-2019, Guidelines for Decision Rules: Considering Measurement Uncertainty Determining Conformance to Specifications.
- ASTM E2782, Standard Guide for Measurement Systems Analysis.
- ASME B89.7.3.1-2019, Guidelines for Decision Rules: Considering Measurement Uncertainty Determining Conformance to Specifications should be considered by the IPT for inclusion in Quality Management Systems requirements.
- SAE AS 13003, Measurement Systems Analysis Requirements; and RM13003 Reference Manual.

Lean Manufacturing: Lean manufacturing focuses on improving manufacturing efficiency by eliminating waste, including reducing lead times and eliminating non-value-added processes—thus improving ease of manufacture and quality. Seven commonly identified types of waste include: transportation, inventory, motion, waiting, overproduction, overprocessing, and defects, commonly referred to as TIMWOOD. Some organizations include wasted skills, talent, or

human potential as an eighth category of waste. To reduce waste, Lean manufacturing tools summarized in Table 8-1 can be applied throughout manufacturing operations to enhance producibility and manufacturability.

Table 8-1. Example Manufacturing Operations Analysis and Lean Manufacturing Tools

Title	Brief Description
Fishbone Diagram (Ishikawa Analysis)	Brainstorm causes of producibility issues. Rank which are most likely or severe to include process flow, potential failure modes, elements of production (labor skills, machines, materials, measurement systems, etc. to understanding producibility.
Process FMEA	A failure modes and effects analysis approach focusing on potential manufacturing or manufacturing assembly processes that may result in manufacturing related defects, scrap, re-work, or system performance failures.
Producibility Assessment Worksheet	A producibility data collection approach to summarize expert opinions on specific producibility topics. The PAW provides input to the IPT on potential producibility issues and to help the design and manufacturing team to develop courses of action for resolution.
Error Proof the Design	Focuses on eliminating or reducing the possibility of error during the manufacturing process. Examples include designing a product and process so that a product can only be assembled the correct way, use of self-aligning parts, or modular components.
Optimize Manufacturing	Achieved through continuous design and process improvement. This may be achieved through trade studies, rapid prototyping, digital engineering, 3D models and digital twins, factory floor modeling and simulation, value stream mapping, and tolerance analysis.
Design of Experiments	Engineering method to deliberately change one or more process variables (or factors) in order to observe the effect, the changes have on one or more response variables. The (statistical) DOE is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions (NIST Handbook, Section 5, “Process Improvement”).
Work Content Analysis	Analysis of what type of work, set up time, labor, and machine time is required. Can be used as a brainstorming tool to determine if producibility issues exist and identify improvement areas such as: time and motion studies, process map, set-up time, machine time, tool change out, assembly time, and workstation design.
Value Stream Mapping	Identify value added, non-value-added and necessary nonvalue added activities to optimize process flow and make items more efficient.
Kanban	Inventory control system that implements “pull” from inventory when needed.
Mistake-proofing (Poka-Yoke)	Mistake proof processes, eliminate potential for human error.
On Time	Control inventory and flow of materials and products to be delivered on time.
5Ss	Organized work environment through these actions: sort, straighten, shine, standardize, sustain (i.e., maintain the 5Ss).
Process Mapping	Map out the production process, understand demand, uptime, and throughput of each operation. Baseline the product needed with the current design. Used for risk analysis tools and to identify opportunities for improvement (ease of assembly, etc.). Process map detailing operation, labor/machine time, uptime, and constraints. Use M&S and digital engineering tools to support the analysis.

Proactive and reactive problem solving, and root cause analysis, involves the ability to rapidly and accurately consider problems and identify solutions using proven root cause analysis and problem-solving techniques. Proactive problem solving addresses the underlying causes of a problem to avoid future challenges, whereas reactive problem solving and root cause analysis responds to problems as they arise.

Example root cause analysis techniques include:

- Pareto chart.
- 5 Whys.
- Fish bone diagram or Ishikawa diagram.
- Scatter plot diagram

The following key references provide additional descriptions of Lean Six Sigma, continuous process improvement tools, root cause analysis, and problem-solving techniques.

Key References

- American Society for Quality (ASQ) at www.asq.org
- The Lean *Six Sigma Pocket Toolbook*, McGraw-Hill, 2007.

8.1 Gage Repeatability and Reproducibility Studies

During manufacturing operations, processes are monitored, including regular data collection intended to keep the process in a "state of control." One of the more effective tools for evaluating measurement variation is a Gage Repeatability and Reproducibility (Gage R&R) study, a common subportion of Measurement System Analysis. Gage R&R is a methodology used to quantify the amount of variation in the measurement system for two major factors: repeatability and reproducibility (ASQ 2023).

Repeatability is a measure of inspection variation under constant conditions (with the same operator, same gages, etc.). For example, when measuring the same part several times under the same conditions, how much will the measurements vary?

Reproducibility is a measure of inspection variation under differing conditions (e.g., differing inspection technicians, or different gages). Reproducibility often assesses the amount of variation in the measurement system that is due to the influence of different operators. For example, is there a difference in measurements due to different inspection personnel and how much difference?

The combined repeatability and reproducibility make up the Gage R&R variability and help identify changes in values related to the measurement system.

The third major source of variation is the part variation. This variation is a measure of how much the parts vary and should be representative of what occurs in production if the project is using the measurement system to control the process.

The combination of these sources of variation is the total variation—a measure of the variation in all the results. Gage R&R can determine the amount of measurement system variation compared with the part/process variation, the source(s) of variation, and thus the suitably of the measurement system to control the process or accept the product.

There are several ways to analyze a Gage R&R study. The most employed methods are:

- Average and Range Method.
- ANOVA Method.
- Evaluating the Measurement Process (EMP) Method.

The Average and Range method has been in use the longest, followed by the ANOVA method. EMP is the most recent.

Detailed analysis can be performed using software such as Mini-Tab or other software packages. Example Gage R&R calculations are provided in Appendix C.

The NIST Handbook (2012) Section 4 provides a detailed discussion on Gage R&R study methodologies, producibility, manufacturability, and quality.

8.2 Design for Six Sigma

Design for Lean Six Sigma (DFSS) focuses on the design of new product or processes using the DMADV (Define, Measure, Analyze, Design, and Verify) or CDOV (Concept, Design, Optimize, and Verify) approach and tools. The goal of DFSS is to design new products and processes that minimize defects, reduce variation, and optimize processes and product while reducing costs. The primary DFSS methodology that many organizations use is the DMADV process as shown in Table 8-2.

Table 8-2. DFSS Steps and Activities

STEP	ACTIVITIES
Define	Define the goal and arrive at Voice of the Customer (VOC)—better understand customers wants and needs.
Measure	Convert the different VOCs to Critical to Quality (CTQs)—an attribute that has a significant impact on actual or perceived quality. Prepare the measurement system (metrics and when, what, how, who, etc.) that will help to understand the performance of CTQ).
Analyze	Analyze the CTQs and convert them into design specification parameters; Analyze the parameters and finalize/prioritize the design components.
Design	Arrive at the design with the required parameters that will meet all the CTQ requirements.
Validate	Make a dry run and check if all the CTQs are designed as expected by the customers; check if all the metrics designed are performing as expected.

8.3 Quality Management Systems and Manufacturability

Quality management includes the coordinated activities to direct and control an organization regarding quality policy, quality objectives, quality planning, quality assurance, and quality improvement. The Quality Management System (QMS) should define the design and manufacturing processes, which significantly influence the quality of systems.

QMS may include industry best practices such as the ISO 9000 series, Quality Management Systems Requirements; AS9100, Quality Management Systems: Requirements for Aviation, Space and Defense Organizations, Safety Management System), or similar. Typical systems engineering processes included in the QMS are:

- Design and development planning – SE management, Failure Modes, Effects, and Criticality Analysis (FMECA), system safety, etc.
- Design and development inputs/outputs – test and evaluation, reviews, and audits.
- Design and development review; verification and validation.
- Control of design and development changes – hardware and software configuration management.
- Risk, issue, and opportunity management.
- Corrective action system.
- Roles, responsibilities, and quality processes.
- Tasks, schedules, and outcomes.

- Standards, requirements, and metrics.
- Quality tools and continuous process improvement.

8.3.1 Advanced Product Quality Planning

Advanced Product Quality Planning (APQP) is a structured approach to product and process design. This framework consists of a standardized set of quality requirements (e.g., SAE AS9145 APQP, and Production Part Approval Process (PPAP)) that enable suppliers to design a product that satisfies the customer. The approach includes five steps or phases:

1. Plan and Define: Links customer requirements (wants and needs) to requirements and includes product and resource planning. APQP does this by capturing customer requirements and incorporating high-level cost, technical, and quality data into a product concept and realization plan.

INPUTS	OUTPUTS

• Voice of the Customer (QFD)
  ○ Market research
  ○ Historical issues
  ○ Team experience
• Business Plan and Marketing Plan
• Product and Process Benchmark
• Product and Process Assumptions
• Product Reliability Studies
• Customer Inputs
• System Requirements Development
• System Architecture Development
	• Design Goals
	• Reliability and Quality Goals
	• Cost of Quality nonconformance targets
	• Preliminary Bill of Material
	• Preliminary Process Flow Chart
	• Preliminary list of Special Product and Process Characteristics
	• Product Assurance Plan
	• Management approval
	• System Requirements Document

2. Product Design and Development: Part of the systems engineering design process and translates requirements into a detailed design, geometry, and tolerances. Design validation is achieved using prototype, development, or production parts in various test environments. FMEA tools would be used during this process.

INPUTS	OUTPUTS
• Design Goals • Reliability and Quality Goals • Preliminary Bill of Materials • Preliminary Process Flow Chart • Preliminary list of Special Product and Process Characteristics • Product Assurance Plan • Management Support • System Requirements Document	• DFMEA • DFMA • Design Verification • Design Reviews • Prototype Build – Control Plan • Engineering Drawings • Engineering Specifications • Material Specifications • Drawing and Specification Changes • New Equipment, Tooling and Facilities Requirements • Special Product and Process Characteristics • Gages and Testing Equipment Requirements • Design Verification and Validation Plans

3. Process Design and Development: Process Flow Charts, PFMEA, and Control Plan Methodologies are tools that would be used during this phase.

INPUTS	OUTPUTS
• Design Failure Mode and Effects Analysis • Design For Manufacturability and Assembly • Design Verification • Design Reviews • Prototype Build – Control Plan • Engineering Drawings and TDPs • Engineering Specifications • Material Specifications • Drawing and Specification Changes • New Equipment, Tooling and Facilities Requirements • Special Product and Process Characteristics • Gages and Testing Equipment Requirements • Validation Plan • Verification Plan	• Packaging Standards • Product/Process Quality System Review • Process Flow Chart • Floor Plan Layout • Characteristics Matrix • Process Failure Mode and Effects Analysis • Pre-Launch Control Plan • Process Instructions • Measurement Systems Analysis Plan • Preliminary Process Capability Study Plan • Packaging Specifications • Production Readiness Review

4. Product and Process Validation: Ensures that the design and production can achieve design requirements and goals and that it can consistently produce uniform, defect-free product at the rate, quantity, and quality required by the customer. SPC, MSA, and process capability studies would be used during this phase.

INPUTS	OUTPUTS
• Packaging Standards • Product/Process Quality System Review • Process Flow Chart • Floor Plan Layout • Characteristics Matrix • Process Failure Mode and Effects Analysis • Pre-Launch Control Plan • Process Instructions • Measurement Systems Analysis Plan • Preliminary Process Capability Study Plan • Packaging Specifications	• Production Trial Run • Measurement Systems Evaluation • Significant Production Run • Preliminary Process Capability Study • Production Part Approval • Production Validation Testing • Packaging Evaluation • Production Control Plan • Quality Planning Sign-Off – formal • First Article Inspection

5. Production Feedback, Assessment, and Corrective Actions: Occurs during ongoing production and attempts to ensure that customer requirements are continuously met using process controls and continuous improvement activities.

INPUTS	OUTPUTS
• Production Trial Run • Measurement Systems Evaluation • Preliminary Process Capability Study • Production Part Approval • Production Validation Testing • Packaging Evaluation • Production Control Plan • Quality Planning Sign-Off – formal	• Reduced Variation ○ SPC and Other Variability Reduction Tools • Improved Customer Satisfaction • Improved Delivery and Service • Effective use of best practice, lessons learned • Maximum Return on Investment • Minimum Waste • Minimum CoQ (yields)

The primary goal of APQP is to facilitate communication and collaboration among engineering activities. APQP ensures the Voice of the Customer (VOC) is clearly understood and translated into requirements, technical specifications, and special characteristics.

An IPT approach should be used in the APQP process. APQP supports the early identification of change, both intentional and incidental. These changes can result in exciting innovation supporting customer satisfaction. When not managed well, the changes translate to failure and customer dissatisfaction. The focus of APQP is use of tools and methods for mitigating the risks associated with change in the new product or process.

Core Tools

- FMEA
- Measurement System Analysis
- SPC

- PPAP

Key Reference

- SAE AS9145, Advanced Product Quality Planning and Production Part Approval Process.

8.3.2 Production Part Approval Process

A PPAP is a structured approval process for new or revised parts, or parts produced from new or significantly revised production methods.

DoDM 4120.24, "Defense Standardization Program Procedures," states,

> Program offices must apply standardization processes to improve parts commonality [and] should ensure that a parts management process is used to reduce the proliferation of parts and associated documentation.

In addition, DoDI 5000.88, Engineering of Defense Systems, states,

> The Program Manager (PM) will ensure that a parts management process is used for the selection of parts during design to consider the life cycle application stresses, standardization, technology (e.g., new and aging), reliability, maintainability, supportability, life cycle cost, and diminishing manufacturing sources and material shortages.

DoD guidance is provided in SD-19, Parts Management Guide.

The PPAP process consists of 18 elements that may be required for approval of production-level parts (not all 18 elements are required). The 18 elements are outlined below:

1. Design Documentation:
    - Includes customer and the supplier's drawings and models. The documentation should also include a copy of the purchase order.
        - Used to confirm that the correct part is being ordered at the correct revision level.
        - The design engineer is responsible for verifying that the two drawings or model source data match and all critical or key characteristics have been identified.
2. Engineering Change Documentation:
    - Required for a change to a part or product. This documentation usually consists of a copy of the Engineering Change Notice (ECN), which must be approved by the customer engineering department.

3. Customer Engineering Approval:
    - When required as part of the PPAP, the supplier must provide evidence of approval by the customer engineering department.
4. Design Failure Modes and Effects Analysis (DFMEA):
    - An examination of design risk by assessing the possible failure modes and their effects on the product or customer and their probability of occurrence. These failure modes can include:
        - Product malfunctions.
        - Reduced performance or product life.
        - Safety and Regulatory issues.
    - The DFMEA is a living document that should be reviewed and updated throughout the product life cycle.
5. Process Flow Diagram: Documents each step in creating the part from start to finish.
    - The diagram outlines the entire process for assembling the component or final assembly in a graphical manner. The process flow includes incoming material, assembly, test, rework, and shipping.
6. Process Failure Modes and Effects Analysis: Identifies all the possible failures within the manufacturing process itself.
    - PFMEA is used to review all steps in the production process to identify any potential process quality risk and then document the applied controls. The PFMEA is also a living document and should be updated even after the product is in normal production.
7. Control Plan: Identifies preventative measures designed to mitigate the possibilities outlined in the PFMEA.
    - The Control Plan is an output from the PFMEA. The Control Plan lists all product Special Characteristics and inspection methods required to deliver products that continually meet the customer quality requirements.
8. Measurement System Analysis Study: Documents the specifications and details of all equipment that will be used.

- MSA studies will include Gage R&R studies on measurement equipment used during assembly or quality control checks. Calibration records for all gages and measurement equipment must be included.

9. Dimensional Layout Analysis (Results): Validates that the measurements on the drawing are correct in relation to the result.

    - The dimensional layout of sample parts is required to validate that the product meets the print specifications. The samples should be randomly selected from a significant production run, usually at least 30 pieces. Each dimension on the drawing is measured on the final assembly to make sure it falls within specification. The results are recorded in a spreadsheet and included within the PPAP submission.

10. Design Verification Plan and Report (DVP&R): Provides a Record of Material/Performance Tests and certification of materials.

    - This element should contain a copy of the Design Verification Plan and Report (DVP&R). The DVP&R is a summary of every validation test performed on the part. It should list every test performed, a description of how the test was performed, and the results of each test.
    - This section may also include copies of all the certification documents for all materials (steel, plastics, etc.) listed on the prints. The material certification shall show compliance to the specific call on the print.

11. Initial Process Studies: Documents all processes that will be used in the fabrication and assembly of a product.

    - Initial process studies will be done on all the production processes and will include SPC charts on the critical characteristics of the product. These studies demonstrate that the critical processes are stable, demonstrate normal variation, and are running near the intended nominal value.

12. Qualified Laboratory Documentation:

    - Provides industry certifications for any lab that participated in completing validation testing (in-house test lab or any offsite contracted test facilities that were used for validation or material certification testing).

13. Appearance Approval Report:

    - The Appearance Approval Inspection (AAI) provides verification that the customer has approved the appearance of the product.

14. Sample Production Parts:
    - Sample production parts are sent to the customer for approval and are stored at either the customer or supplier's site after the product development is complete. A picture of the production parts is usually included in the PPAP documentation.
15. Master Sample:
    - A master sample is a final sample of the product that is inspected and signed off by the customer and stored at the supplier site.
16. Checking Aids:
    - A detailed list of checking aids, tools used to inspect, test or measure parts during the production/assembly process. The list should include the calibration schedule and frequency for the tool. Checking aids include check fixtures, contour, variable and attribute gages, models, or templates.
    - MSA may be required for all checking aids based on customer requirements.
17. Records of Customer Specific Requirements:
    - Any special customer requirements. Customer-specific requirements for bulk materials are recorded on the Bulk Material Requirements Checklist.
18. Part Submission Warrant (PSW):
    - A summary of the entire PPAP submission. A PSW is required for each part number unless otherwise stated by the customer and includes:
        - The reason for submission (design change, annual revalidation, etc.).
        - The level of documents submitted to the customer.
        - Declaration of part conformity to customer requirements.
        - A section provided for any required explanation or comments.
        - Supplier authorized person signature along with contact information.
        - An area for the customer to indicate disposition of the PPAP.

Key References

- SD-19, Parts Management Guide.
- MIL-STD-11991B, DoD Standard Practice General Standard for Parts, Materials, and Processes.
- DI-STDZ-81993, Parts, Materials, and Processes Management Plan.

- SAE AS9145, Advanced Product Quality Planning and Production Part Approval Process.

8.3.3 Counterfeit Parts Prevention

To facilitate manufacturing operations, M&Q practitioners should actively engage to monitor and manage and prevent the introduction of counterfeit parts. DFARS 246.870-3 prescribes the use of clauses 252.246-7007, "Contractor Counterfeit Electronic Part Detection and Avoidance System," and 252.246-7008, "Sources of Electronic Parts," when procuring electronic parts or end items that contain electronic parts.

8.3.4 Quality Function Deployment

The Quality Function Deployment (QFD), also known as a House of Quality, is a graphical technique as summarized in Figure 8-2 that can be used throughout development to show the relationship between system requirements and proposed design solutions. QFD identifies trade-offs, shows where design solutions may conflict, and shows where proposed solutions will not meet requirements.

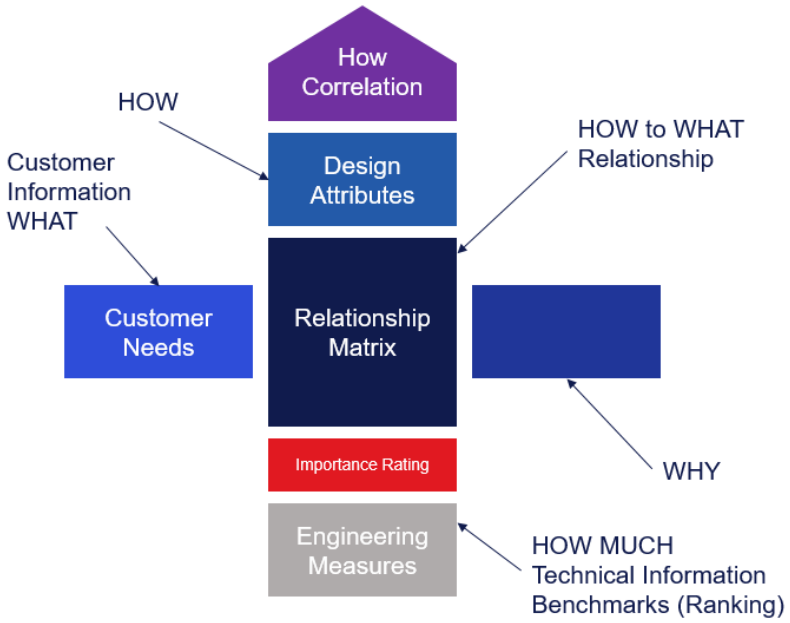


Figure 8-2. QFD House of Quality Concept

A series of QFDs can be used to translate customer requirements, or VOC, into measurable design targets and drive them from the assembly level down through the sub-assembly, component, and production process levels.

The outputs ("how") of one cycle become the inputs ("what") of the next cycle. QFD may be employed incrementally through the system development process as shown in Table 8-3.

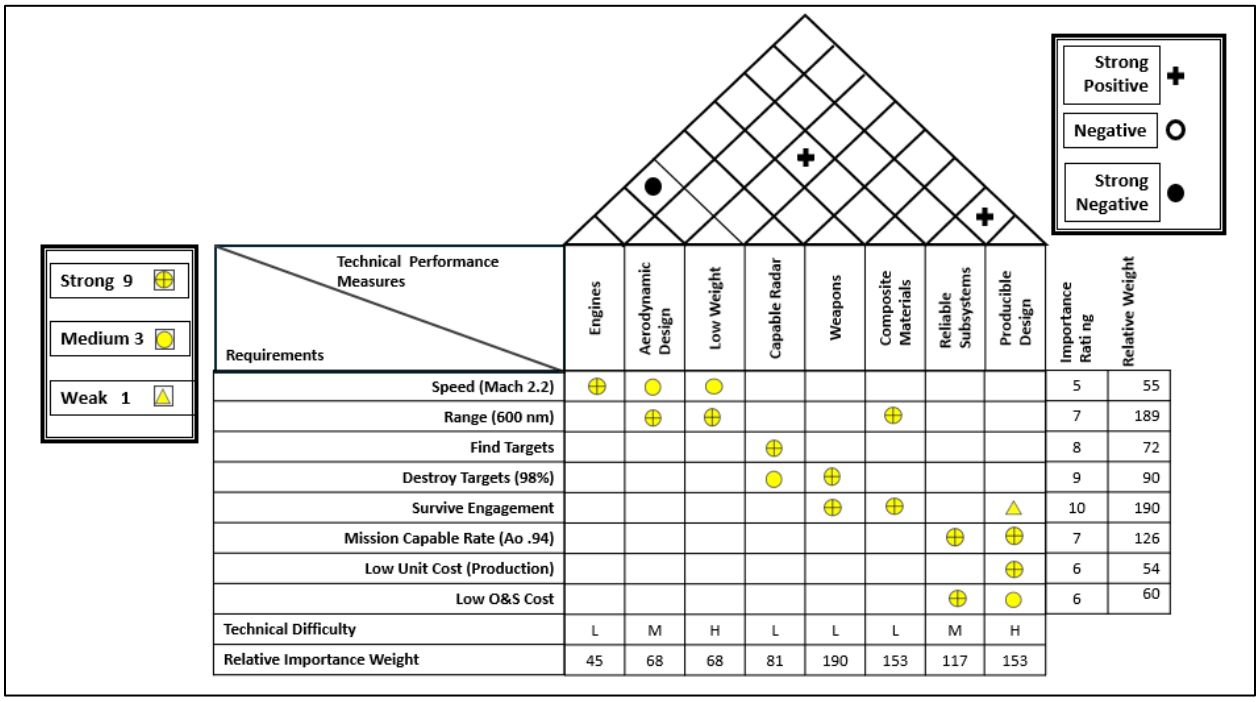
Table 8-3. QFD throughout Producibility Engineering

Project Activity	QFD Objective	Inputs ("What")	Outputs ("How")
Concept / Pre-MDD	Product planning: Identify customer demands and develop those into technical/system requirements	Customer needs	Technical requirements / System Requirements
PDR	System, subsystem, and parts requirements: Decompose technical/system requirements to design requirements	Technical /System requirements	Design Requirements
CDR	Process planning: Decompose the product design requirements to the manufacturing process requirements. Iteratively, if manufacturing process requirements cannot be met- it may influence product design- changes to features to ensure its producible on the available manufacturing process	Design Requirements	Process Requirements
PRR	Process control: Decomposes manufacturing process requirements to control requirements, so that the team identifies what needs to be inspected/monitored to ensure the production process is producing the right parts	Process Requirements	Control Requirements informs the SPC plan

Below is an example House of Quality using QFD to develop a new design concept for a military aircraft. The QFD tool allows engineers to:

1. Identify customer requirements (what).
2. Prioritize customer needs (importance rating).
3. Identify design solutions or How (weight, dimensions, horsepower, etc.).
4. Identify interrelationships between What's and How's (center section).
5. Determine relative importance of What's (weighted score).
6. Identify design conflicts in the roof (car weight vs fuel consumption).
7. Set target values for design solutions (bottom three rows).

Figure 8-3 provides a representation of QFD using a House of Quality matrix.



Requirements \ Technical Performance Measures	Engines	Aerodynamic Design	Low Weight	Capable Radar	Weapons	Composite Materials	Reliable Subsystems	Producible Design	Importance Rating	Relative Weight
Speed (Mach 2.2)	⊕	○	○						5	55
Range (600 nm)		⊕	⊕			⊕			7	189
Find Targets				⊕					8	72
Destroy Targets (98%)				○	⊕				9	90
Survive Engagement					⊕	⊕		△	10	190
Mission Capable Rate (Ao .94)							⊕	⊕	7	126
Low Unit Cost (Production)								⊕	6	54
Low O&S Cost							⊕	○	6	60
Technical Difficulty	L	M	H	L	L	L	M	H		
Relative Importance Weight	45	68	68	81	190	153	117	153		

Figure 8-3. Notional QFD Assessment of Requirements

QFD supports producibility by using multidisciplinary engineering teams to exercise the systems engineering process from requirements allocation through design, build, test, and deployment to help influence the design of, plan for, and execute production plans.

8.4 Producibility, Manufacturability, and Reliability and Maintainability

Product R&M and producibility are interrelated and interdependent. For example, the producibility principle of "simplicity of design" almost always benefits producibility, reliability, and quality. On the other hand, manufacturing processes on the factory floor may introduce potential failure modes into the system, affecting product quality and system reliability. System reliability failures experienced during operations can drive changes to system design, resulting in the need to update manufacturing processes. R&M life cycle activities (Figure 8-4) are often synergistic with producibility and manufacturability considerations and tools. R&M practitioners should participate and collaborate with M&Q practitioners in IPT and IPPD activities.

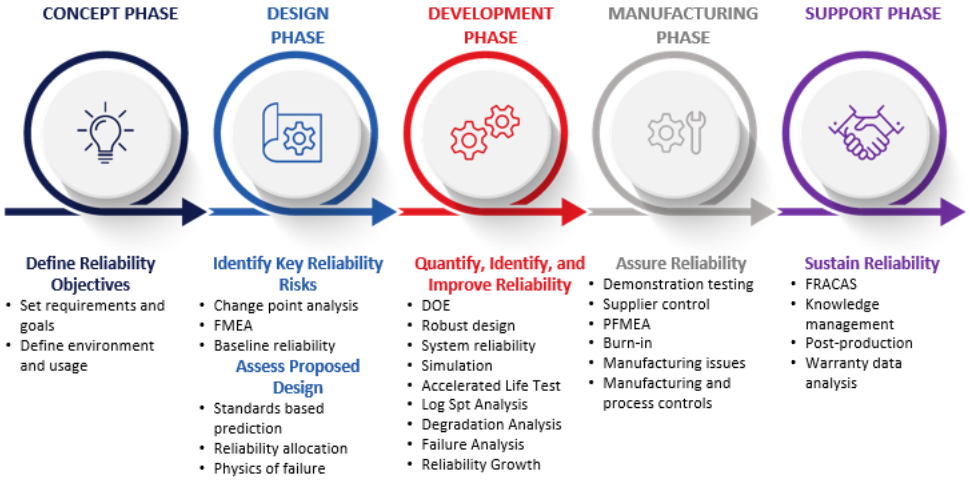


Figure 8-4. R&M over the Life Cycle

8.4.1 Failure Modes and Effects Analysis and Failure Modes, Effects, and Criticality Analysis

Failure Modes and Effects Analysis (FMEA) and Failure Modes, Effects, and Criticality Analysis (FMECA) are reliability evaluation and design techniques that examine potential failure modes within a system and its equipment to determine the effects on equipment and system performance.

A FMEA identifies the following:

- Failure Mode: The ways in which a product can fail.
- Failure Effect: The consequences of that failure mode.
- Failure Cause: The possible cause(s) of that failure mode.
- Failure Analysis: An assessment of the severity, frequency, and chance of detection.

FMEA is one set of analysis that informs the FMECA. FMECA adds to the FMEA by ranking failure according to severity or consequence. Specifically the FMECA

> …identifies independent single item failures and the resulting potential impact on mission success, performance, safety, and maintainability. The FMECA promotes corrective actions by identifying potential failure risk and maintainability issues in order that appropriate corrective actions may be taken early to eliminate or control high risk items to improve operational readiness and reduce life cycle cost. The FMECA also establishes the baseline engineering information to identify and eliminate or control all failure modes throughout the system life cycle. The FMECA analytics establish the basis for fault detection, fault isolation, operator and maintainer failure recognition,

depot test parameters and lay-in repair parts." (Source Data Item Description, DI-SESS-81495B)

8.4.2 Design Failure Modes and Effects Analysis

Design FMEA (DFMEA) is a technique used to analyze, before the manufacturing phase of development, a part's design to identify potential failures, errors, and defects and their effect on cost and risk. DFMEA focuses on product design.

Early IPT support is critical to the success of DFMEA efforts and requires input from various functional engineers (design, mechanical, electrical, manufacturing, quality, etc.) and other stakeholders (maintainers and logisticians). As part of the FMEA process, manufacturing processes should also be reviewed for potential impacts on product reliability.

8.4.3 Process Failure Modes and Effects Analysis

PFMEA is a technique to analyze manufacturing processes to identify potential failures, errors, and defects and their effect on cost and risk. M&Q, industrial engineers, and process engineers look at each process step to identify sources of errors that could occur from manpower, machines, materials, methods, measurements, or the environment. PFMEA requires the use of a process map or process flow diagram to conduct the analysis and uses key product characteristics as an input.

A special characteristic is a design feature or other feature of a product that may result in manufacturing or assembly variation and introduces risk to the manufacturing process. Design teams should identify these characteristics as part of the PFMEA process. M&Q specialists should monitor these characteristics during the manufacturing process.

SAE J1739 Potential Failure Modes and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA is the industry standard for FMEAs and PFMEA processes. As a best practice, manufacturing engineers should include this standard in contract requirements.

A PFMEA approach evaluates each process step (process flow diagram) to identify, assess, mitigate, and prevent potential failure modes created by manufacturing and assembly processes.

- Severity: Impact of the failure or error in the manufacturing process.
- Occurrence: Chance of a failure occurring.
- Detection: Chance of a failure being detected.
- Overall risk assessment (Risk priority number).

Potential sources of process failures include:

- Method and procedure errors.
- Material, part, and component defects.
- Measurement system errors.
- Manufacturing operator and worker variation.
- External factors (e.g., temperature, humidity, dust)

As a best practice, there should be two-way feedback between the FMEA and PFMEA.

8.4.4 Failure Reporting, Analysis, and Corrective Action System

FRACAS is used to promote and improve the R&M of a system. FRACAS provides a disciplined closed-loop process for solving R&M issues at the design, development, production, and fielding phases of the system life cycle. It is an essential element of every reliability program (Figure 8-5).

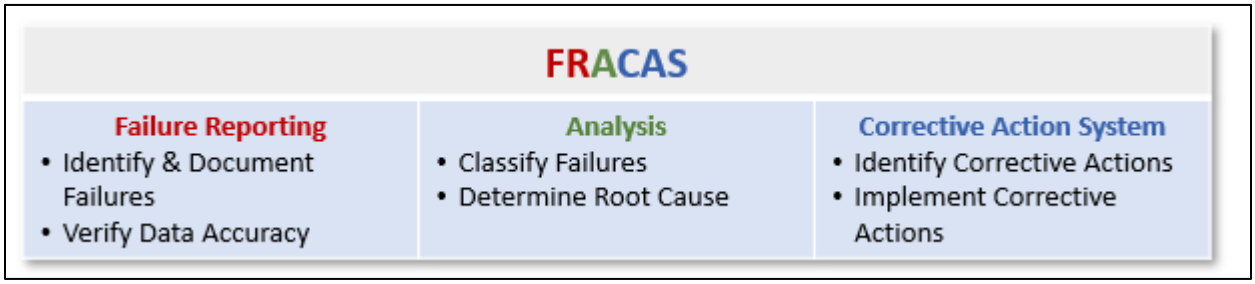


Figure 8-5. FRACAS Overview

Key References

- DoD Reliability and Maintainability Body of Knowledge (RMBoK).
- SAE J1739 Potential Failure Modes and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA.
- SAE AS 13004, Process Failure Modes and Effects Analysis and Control Charts.
- MIL-HDBK-470A, Designing and Developing Maintainable Products and Systems, Rev. A, Notice 2, 2012.
- MIL-HDBK-2155, Failure Reporting, Analysis and Corrective Action Taken.
- Data Item Description, DI-SESS-81495B, FMECA.

FMEA																
Identification Number	Item/ Functional Identification Nomendature	Function Number	Function	Functional Failure Letter	Functional Failure Description	Failure Mode & Causes	Mission Phase/ Operational Mode	Failure Effects			Failure Detection Method	Isolation	Compensating Provisions (Design/Operator)	Severity Classification	Basic Maintenance Actions	Remarks
								Local Effects	Next Higher Effects	End Effect						
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

Figure 8-6. Failure Modes and Effects Analysis Worksheet

9 ADVANCED MANUFACTURING TECHNOLOGY CONSIDERATIONS

9.1 Digital Manufacturing and Ease of Manufacture

Digital manufacturing is an integrated approach to manufacturing using digital data, computer systems, and internet capabilities to facilitate automation across manufacturing operations. Digital manufacturing enables producibility concepts such as DFMA, advanced manufacturing (Industry 4.0), and Lean manufacturing to optimize processes, improve process capability, increase product quality, improve efficiency, and reduce schedule and cost. Figure 9-1 depicts digital manufacturing, which uses digital tools with an impact on key elements of producibility and manufacturability: the "5Ms"—manpower, machines, methods, materials, and measurement.

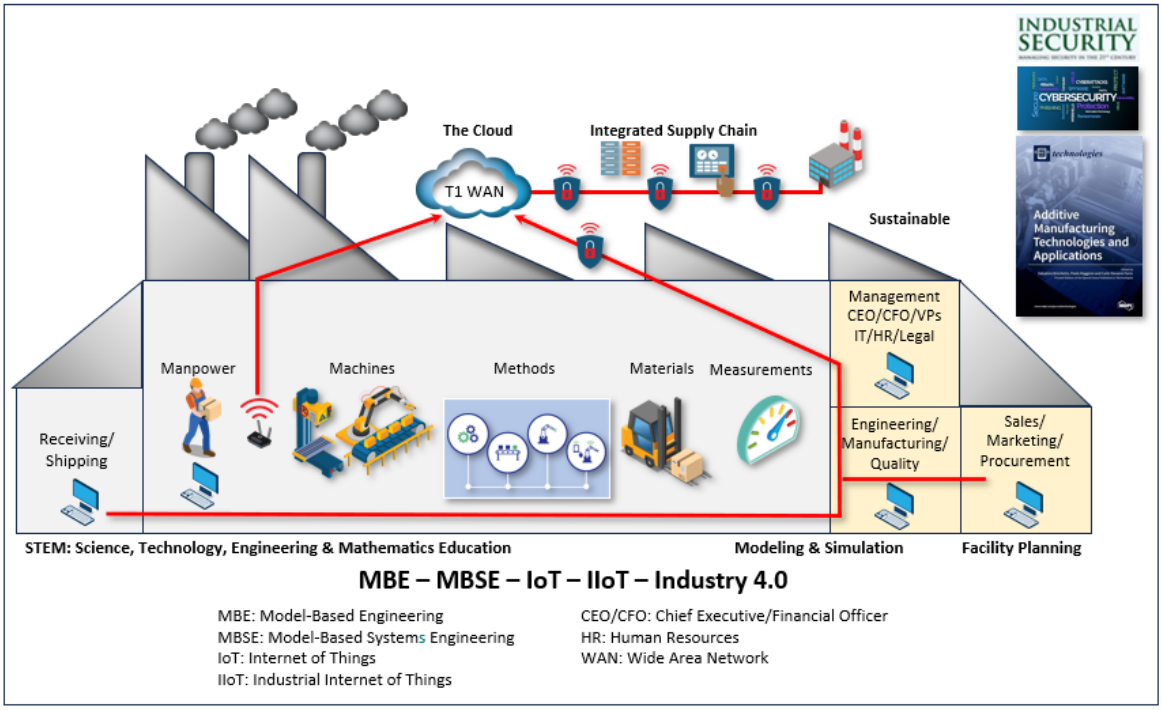


Figure 9-1. Emerging Digital Factory

As summarized in the 2022 White House, National Science and Technology Council, National Strategy for Advanced Manufacturing, digital manufacturing is defined as follows:

> Digital manufacturing involves the use of an integrated, computer-based system incorporating simulation, 3D visualization, analytics, and collaboration tools to create product and manufacturing process definitions simultaneously. Technology-based productivity improvements have consistently driven job growth by providing new tools that increase the productivity of factory floor workers. New scientific understanding and widespread high-speed computing and communications technologies now enable tremendous new productivity gains, but only if information technology can be integrated with operational technology.

The report further states,

> The promise of digital manufacturing is guaranteeing high uptime and high-quality parts by monitoring and controlling every stage of the production process. While existing methods can be used to bring almost any manufacturing process under control, implementations are often expensive and time-consuming, lack generality, and are not fully dependable, limiting their application to the most expensive or highest volume products. New methods are needed to transition smart manufacturing from a collection of heroic demonstrations to routine and widespread use. The ultimate realization of smart manufacturing will result from the implementation of a digital twin, a computational model that reflects reality so precisely that it can accurately anticipate and avoid faults before they occur. Implementation of digital twins requires ubiquitous sensing of critical process parameters that will be facilitated by the production of low-cost, miniature, and accurate sensors, and process models that account for uncertainty. (C-9)

9.2 Digital Engineering and Modeling and Simulation

The DoD Military Handbook Digital Engineering and Modeling Practices (MIL-HDBK-539) defines digital engineering as "an integrated, computation-based approach that uses authoritative sources of system data and models as a continuum across disciplines to support life cycle activities."

DoDI 5000.97 states, "Digital engineering must be addressed in the acquisition strategy, including how and when digital engineering will be used in the system life cycle and expected benefits of its use" (page 3).

DoDI 5000.97 para 3.5.a.3 further states, "Programs will update and maintain the digital model(s) throughout the system life cycle and maintain configuration management (i.e., version control). These updates, conducted within the digital models, will provide program stakeholders, including digital model developers, simulation users, testers, and other engineering and program management personnel, with the ability to extract and analyze consistent and up-to-date system information. Digital models and simulations must be updated using all relevant real-world data throughout the system life cycle since they will be **used to make decisions, inform manufacturing,** generate software code, etc." (bold font added).

In addition, DoDI 5000.88 requires the PM to develop a "…digital engineering implementation plan to include model elements, element relationship diagrams, activity diagrams, block definition diagrams, and use case diagrams." In accordance with DoDI 5000.88, Para 3.4.a.(3)(m) and the SEP Outline, the implementation plan must be included in the SEP. DoDI 5000.01 also requires the SEP to be included with the RFP.

Manufacturing engineers should ensure that producibility digital tools, models, and data are included in the program's digital engineering implementation plan and data architecture. This information should be integrated into the program business processes, engineering data requirements, and life cycle data needs (e.g., digital thread). This planning facilitates integration and transfer of producibility digital information across all life cycle phases from design, development, production, test, operations, sustainment, and disposal. As the digital ecosystem and data architecture are defined, manufacturing engineers should consider the following example data elements (Table 9-1) to support producibility efforts.

Table 9-1. Example M&Q Related Data Elements

Example Data Elements			
Engineering Design Data	**Technical Product Data**	**Manufacturing & Quality Data**	**Enterprise Data**
• Producibility Analysis • Computer Aided Design (CAD) Data • Special Inspection Equipment • Packaging Instructions • Special Tooling • Engineering Analysis	• Digital Drawings • Digital Models • Specifications • Standards • Critical manufacturing Processes • CM Data • Engineering Change Notices • Design Data	• Manufacturing Floor Layout M&S • Pilot Line • Production Line • Industrial Engineering Data • CAM Data • Work Instructions • PFMEA • Machine Status • Defects, Scrap, Re-work Data • First Article Test • SPC Data • Time Studies • Learning Curves • Inventory Management • Industrial Control Systems • Non-Conformance • DMSMS	• Customer Demand (required rates and quantities) • WBS • FRACAS • Supplier data • Cost Data

A Technical Data Package (TDP) is the authoritative technical description of an item. This technical description supports the acquisition, production, inspection, engineering, and logistics

support of the item. The description defines the required design configuration and performance requirements, as well as procedures required to ensure adequacy of item performance. It consists of applicable technical data such as models, engineering design data, associated lists, specifications, standards, performance requirements, quality assurance provisions, software documentation, and packaging details. This definition is as specified in MIL-STD-31000 (MIL-HDBK-539).

- Native Computer Aided Design (CAD) TDP data: Data as created in its original authoring software format.
- Neutral CAD TDP data: Data derived from the native format and converted into a format that can be imported into other CAD software.
- Viewable CAD TDP data: Data derived from the native format and converted into a format that can be displayed by widely available software for the purpose of defining design intent in a human readable format.
- Product and Manufacturing Information (PMI): Data that includes GD&T annotations, surface finish and material specifications necessary to manufacture product components and assemblies. Industry standards for defining PMI include ASME Y14.41, Digital Product Data Definition Practices, ASME Y14.5 2018 Dimensioning and Tolerancing Standard, and ISO 1101:2004 Geometrical Product Specifications, Geometric Tolerancing. PMI data created on a 3D CAD model can be exported to neutral formats such as ISO 10303 Standard for the Exchange of Product Model Data (STEP) 3D PDF.
- Computer-Aided Process Planning (CAPP): Translates design information into the process steps and instructions to efficiently manufacture products. The planning begins with engineering drawings, specifications, parts, or material lists and a forecast of demand. Computer-aided process planners develop detailed process plans to include estimating man-hours, tooling, and material as well as determining which machines will be used to accomplish work, and sequence of operations for parts on various machines. Work is phased by operations and machine, giving detailed instructions of the workflow and how it is to be accomplished.

In addition, M&Q specialists should provide input to the IPT on the program's PLM approach. The PLM is a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information (product data) across the extended enterprise, and spanning from product concept to end of life, integrating people, processes, business systems, and information (MIL-HDBK-539).

Key References

- DoDI 5000.97, Digital Engineering.
- DoD Digital Engineering Strategy.

- DoD Data Strategy.
- MIL-HDBK-539, DoD Digital Engineering and Modeling Practices Handbook.
- MIL-STD-31000, Technical Data Package.
- ISO 10303, Standard for the Exchange of Product Model Data.

Modeling and Simulation

Manufacturing simulation is the use of computer modeling to test manufacturing methods and procedures – including processes such as production, assembly, inventory, and transportation. Simulation software can be used to predict the performance of a planned manufacturing system and to compare solutions for any problems discovered in the system's design. This approach makes manufacturing simulation a significantly competitive capability, allowing manufacturers to test a range of scenarios before buying tooling, reserving capacity, or coordinating other expensive production resources. By using simulation software to determine exactly what is needed, the manufacturer can avoid problems during production while also reducing scrap and rework. Various types of factory M&S tools currently available include, but are not limited to, the following areas:

- Producibility Analysis and Ergonomics.
- Process Planning.
- Production Planning and Scheduling.
- Line Balancing and Bottleneck Analysis.
- Capacity Planning.
- Predictive Analytics and Optimization.
- Facility Planning, Layout and Design.
- Virtual Factory Mockup.

As a best practice, SAE AS6500A "Manufacturing Management Program" requires organizations to analyze manufacturing processes using M&S techniques to identify potential bottlenecks, confirm the achievability of planned cycle times, evaluate impacts of process variables, and estimate required quantities of tooling, people, and inventory. Refer to MIL-HDBK-539 for a summary of digital engineering and manufacturing M&S tools and software packages.

Example M&S capabilities that contribute to producibility planning, engineering, and execution are included in Table 9-2. Note: the tools identified are for illustration purposes and their inclusion does not constitute endorsement by DoD or the U.S. Government.

Table 9-2. Example DE and M&S Tools

M&S Function	Producibility Application
Monte Carlo simulation	Performs risk analysis by building models of possible results by substituting a range of values using probability distributions for factors of uncertainty. Program offices should periodically perform a schedule analysis against their baseline to determine if risks exist (tied to Earned Value Management System Schedules).
Statistical Analysis	Analyze data in a variety of formats, including QFD, DOE, FMEA, etc. It performs statistical analysis tests including ANOVA, t-test, F-test, and regression analysis, histograms with Cp and Cpk, Pareto charts.
Data Analysis	Tool for data mining by digging deeper, it will explore and graph data dynamically, developing visualizations that tell the story of your data.
Simulation Software	Factory floor M&S tool for building and executing dynamic models of systems so that you can see how they perform. Simio "acts out" and displays a 3D animation of the behavior of your system over time. Simio lets you see your proposed systems in operation before you build them or change them. Simio software also fully supports both discrete and continuous systems, along with large scale applications based on agent-based modeling.

9.3 Model-Based Systems Engineering

Model-based systems engineering (MBSE) is a methodology that focuses on creating and exploiting domain models as the primary means of information exchange between engineers, rather than document-based information. According to the International Council on Systems Engineering (INCOSE), MBSE is the "formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." MBSE is a methodology that focuses on creating and exploiting domain models as the primary means of information exchange between engineers, rather than document-based information.

Producibility may be improved using the following MBSE technologies:

- Computer-Aided Design (CAD): A process of digitally creating design simulations of products in 2D or 3D, complete with scale, precision, and physics properties, to optimize and perfect the design before manufacturing. CAD is used to create, modify, analyze, or optimize a design. Some CAD tools include CREO, Solidworks, CATIA, XM, etc. To support producibility analysis and engineering, CAD allows engineers to perform tolerance analysis, mass property calculations, and finite-element modeling and visualization.

- Computer-Aided Manufacturing (CAM): Involves the use of digital data, software, and computer-controlled factory machinery to create products with high quality by automating and optimizing manufacturing processes. CAM can be used to address production facilities, work centers and stations, processes, methods, equipment maintenance, and materials handling, etc. M&Q personnel should provide input to the digital implementation plan and PLM approach to ensure CAM is integrated with the program's CAD and PLM architecture.

9.4 Advanced Manufacturing

The National Strategy for Advanced Manufacturing (National Science and Technology Council, 2022) defines advanced manufacturing as "the innovation of improved methods for manufacturing existing products, and the production of new products enabled by advanced technologies" (page 2). Current implementation of advanced manufacturing is driven by advances in digital engineering, automation, artificial intelligence, materials science, and machine learning. Industry 4.0 summarizes a concept emphasizing the growth in digital technology to automate manufacturing operations with interconnectivity through large-scale machine-to-machine communication, Internet of Things/Industrial Internet of Things (IoT/IIoT), access to real-time data, and the introduction of cyber-physical systems. Figure 9-2 summarizes key Industry 4.0 technologies.

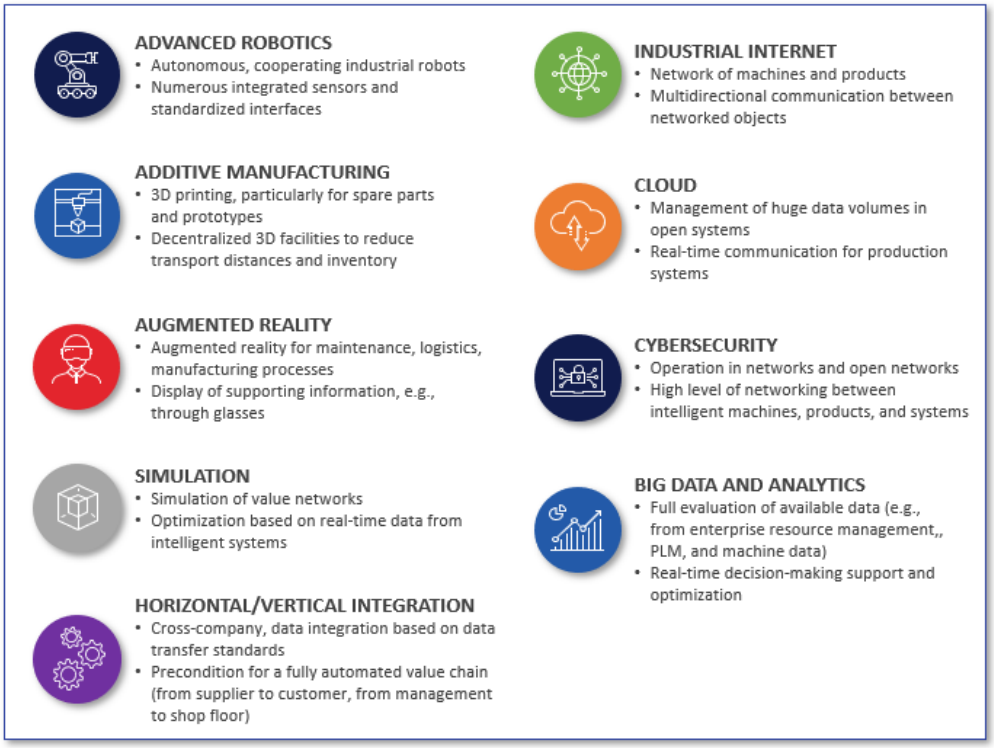


Figure 9-2. Example Industry 4.0 Technologies

Industry 4.0 empowers manufacturing engineers with increased visibility, understanding, and potentially control of the manufacturing operations and leverages digital data to increase productivity. It is also characterized by advanced manufacturing technologies and processes that significantly improve producibility. Industry 4.0 contributes to producibility by automating and improving processes as summarized in Table 9-3.

Table 9-3. Industry 4.0 Producibility Applications

Technology	Description	Producibility Benefits/Applications
Advanced Robotics	Advanced robots are automated, programmable, automated systems designed to perform a specific task. Typical manufacturing applications: welding, painting, assembly, disassembly, pick and place, packaging and labeling, material handling, product inspection.	• High speed, endurance, precision. • Hazardous, repetitive operations. • Flexible, reconfigurable. • Up to 6 Degrees of Freedom motion. • Decrease required manufacturing labor and skill levels.
Additive Manufacturing (3D Printing)	Production of a three-dimensional object from a digital 3D or computer aided design model. AM processes include applying materials in incremental layers to create fully developed three-dimensional parts.	• Production of parts with complex geometries not possible by conventional machining. • Rapid prototyping of physical parts and assemblies. • Allows for designs with few parts. • Parts can be inspected during the manufacturing process as each material layer is added.
Augmented Reality/Virtual Reality	Augmented Reality is an interactive technology that combines real world with and computer-generated content. Virtual Reality (VR) is a simulated experience that uses 3D eye displays (wearables, goggles) to provide the user with a feel of a virtual world. AR/VR gives designers and production workers with greater abilities to build product while incorporating incoming information more efficiently.	• Substitute paperwork instructions and manuals with digital instructions on the manufacturing workers display. • Rapidly update digital work instructions and technical data. • Reduce workers' need to look at other displays and manuals. • Provide additional information to the worker such warning of hazardous conditions. • Display current machine data and status.
Modeling and Simulation	Use of mathematical models to develop data for decision making. For manufacturing systems, simulation software can be used to predict the performance of the overall manufacturing system (factory floor) and manufacturing processes to evaluate changes to parts of the system to compare solutions and improve overall production efficiency—improving producibility.	• Provide engineering information to make the design more producible. • Simulate the factory floor design, workflow and evaluate changes to the manufacturing system.

Technology	Description	Producibility Benefits/Applications
		• Simulate, measure, and analyze factors such as: Production capacity, rates, inventory level, time spent in queue, and use rates of machines and workers.
Horizontal/Vertical Integration	Data integration and automation across and between organizations in the supply chain and manufacturing process.	• Increase visibility into supply chains. • Reduce inventory and production costs.
Industrial Internet of Things (IIoT)	The Industrial Internet of Things, or IIoT. represents the network of interconnected systems and devices to allow data collection, exchange, and analysis.	• Facilitates digitization of production. • Increase visibility to manufacturing and producibility information across the enterprise. • Allows new technologies to be introduced to the manufacturing process (i.e., 3D printing, VR/AR). • Predictive maintenance of manufacturing equipment. • Increased productivity.
Cloud Computing/Storage	Cloud computing allows on-demand access to data, via the internet, to computing resources hosted at a remote data center managed by a cloud services provider without active management by the user.	• Allows for higher degree of automation. • Provides manufacturing engineers and manufacturing workers with access to large amounts of near real-time manufacturing and producibility data and information.
Cybersecurity	Manufacturers increasingly rely on data, information, and technologies to run their operations. Defending these assets from disclosure, modification, disruption, or improper use is a challenging but critical aspect of operating a business.	• A failure to protect manufacturing software and other production IT assets from outside threats constitutes potential risks to production operations, and hence producibility itself.
Big Data and Analytics	Many major industries use different types of data analysis to make more informed decisions around product strategy, operations, sales, marketing, and customer care. Big Data analytics makes it possible for any organization that works with large amounts of data to derive meaningful insights from that data.	• Examples related to production operations and producibility issues include Product development, supply chain management, and operations. Analyzing financial data helps organizations detect and reduce hidden operational costs, in turn saving money and increasing productivity.
Blockchain supply chain management	A blockchain is a distributed database or ledger that is shared among the nodes of a computer network. As a database, a blockchain stores information electronically in digital format to guarantees the fidelity and security of data	• Improved supply chain management.

Technology	Description	Producibility Benefits/Applications
	records, generating trust without the need for a third party.	• Ability to track the origin of parts and component (i.e., reduced counterfeit parts, improved visibility into supplier quality). • Producibility example: When an inspection system detects a defect, the source of that defect can be traced rapidly. This gives production managers and members of the supplier network the ability to identify the scale and nature of the overall problem and to determine a course of remediation in short time.

9.5 Quality and Emerging Technologies

Like digital engineering and digital manufacturing, advanced quality processes and tools are also rapidly evolving to automate quality operations, emphasizing interconnectivity through large-scale machine-to-machine communication, IoT/IIoT, access to real-time data, and the introduction of cyber-physical systems. ASQ has termed this as "Quality 4.0," in which the emphasis shifts from production to system design and integration with business systems.

- Digitization is used to optimize signal feedback and process adjustment, and adaptive learning supports self-induced system corrections.
- Quality shifts focus from the process operators to the process designers.
- Machines learn how to self-regulate, managing productivity and quality.

Table 9-4 outlines potential benefits and application of digital engineering applications for quality activities.

Table 9-4. Quality 4.0 Potential Producibility Applications

Technology	Description	Producibility Benefits/Applications
Artificial Intelligence (AI)	Computer vision, language processing, chatbots, personal assistants, navigation, robotics, making complex decisions	• AI capabilities will make manufacturing more responsive.
Big data infrastructure	Easier access to data sources, tools for managing and analyzing large data sets without having to use supercomputers (such as MapReduce, Hadoop, Hive, and NoSQL databases)	• Allows quicker more accurate analysis of quality data.
Blockchain	Increasing transparency and auditability of transactions (for assets and information),	• Traceability enhances integrity of supply chain.

Technology	Description	Producibility Benefits/Applications
	monitoring conditions so transactions don't occur unless quality objectives are met.	
Deep Learning	Image classification, complex pattern recognition, time series forecasting, text generation, creating sound and art, creating fictitious video from real video, adjusting images based on heuristics (e.g., make a frowning person in a photo appear to smile, for example).	• Enhanced interface with operators and ability to rapidly adapt production processes.
Enabling technologies	Affordable sensors and actuators, cloud computing, open-source software, augmented reality (AR), mixed reality, virtual reality (VR), data streaming (such as Kafka and Storm), 5G networks, IPv6, IoT.	• Real time monitoring of manufacturing environment. • In-process Inspection. • Remote inspection.
Machine Learning	Text analysis, recommendation systems, email spam filters, fraud detection, classifying objects into groups, forecasting.	• Real time learning and adaptations of manufacturing processes to reduce defects and variation.
Data Science	The practice of bringing together heterogeneous data sets for making predictions, performing classifications, finding patterns in large data sets, reducing large sets of observations to most significant predictors, applying sound traditional techniques (such as visualization, inference, and simulation) to generate viable models and solutions	• Ability to discern patterns in large disparate data set used to optimize manufacturing cells.

Key References

- DoDI 5000.93, Use of Additive Manufacturing in the DoD.
- DoDI 5000.94, Use of Robotic Systems for Manufacturing and Sustainment in the DoD.
- MIL-A-70625A, Military Specification, Automated Acceptance Inspection Equipment Design, Testing and Approval, and Notice 2.
- ASQ and ASQ "Quality 4.0."

10 CONTRACTING FOR PRODUCIBILITY AND MANUFACTURABILITY

Producibility activities are driven by requirements specified in the contract. As a best practice, M&Q personnel should engage with the program IPTs to provide input to the RFP and participate in proposal review teams. Example suggested producibility-related tasks to consider include the following:

- Analyze the manufacturing, industrial base data, and producibility results from the AoA and system concepts trade-off as a basis for initial RFP requirements.
- Specify appropriate producibility requirements for the Statement of Work (SOW), Contract Data Requirements List items (CDRLs), Data Item Descriptions (DIDs), contract clauses, and source selection criteria.
- Define standards and approach for the program's Manufacturing Management System and Quality Management System (e.g., AS6500A, ISO 9001, AS9100, FAA quality standards).
- Include contractor requirements for producibility planning, producibility engineering, producibility analysis, and measurement and continuous process improvement, such as:
    - Conduct producibility analyses.
    - Identify and manage key and critical characteristics in the Technical Data Package.
    - Implement a Variability Reduction program to reduce part-to-part variation of KCs and CCs.
    - Require conduct of Process Failure Modes and Effects Analysis on manufacturing processes.
    - Identify producibility risk:
        - Integrate manufacturing risk management activities into the contractor's risk management program management process.
        - Conduct and document manufacturing feasibility assessments for each competing design alternative under consideration.
        - Identify MRL targets and document manufacturing risks through the MRL assessments.
- Measure and improve manufacturing operations:
    - Production scheduling and control.
    - Manufacturing surveillance.
    - Continuous improvement.
    - Process control plans.

  - Process capabilities.
  - Production process verification.
  - First Article Inspections and First Article Tests (AS 9102).
  - MRL assessments.
- Supplier management and quality management approaches.

Appendix D of this guide provides specific suggested RFP considerations to implement producibility planning, engineering, and implementation.

Key References

- MIL-HDBK-245E, Preparation of Statements of Work.
- Guide for Integrating Systems Engineering into DoD Acquisition Contracts (Forthcoming).
- Best Practices for Using Systems Engineering Standards (ISO/IEC/IEEE 15288, IEEE 15288.1, and IEEE 15288.2) on Contracts for Department of Defense Acquisition Programs.
- SD-26, DMSMS and Parts Management Contracting Guide.

APPENDIX A: COMMON PRODUCIBILITY-RELATED TOOLS AND TECHNIQUES

Table A-1. Common Producibility Tools and Techniques

Tool	Description	Producibility Benefits/Application
Design Failure Modes and Effects Analysis (DFMEA)	A technique used to analyze, prior to entering the manufacturing phase of development, a part's design to identify potential failures, errors, and defects and their effect on cost and risk.	Used during the design stage and focuses on product design to enhance producibility.
Design for Assembly (DFA)	DFA eases assembly by ensuring that the design is simple, has fewer parts, and minimizes difficult operations, making it easier and faster to fabricate systems with fewer defects and delays.	Promotes optimized design to ensure a product are assembled easily with high quality and low cost.
Design for Ergonomics (DFE)	Focuses on human factors of the production workforce when designing products and manufacturing processes. Good ergonomics help to reduce operator induced errors by minimizing repetitive motion injuries.	Simplifies the product structure and makes the design less complex, which can enhance producibility.
Design for Manufacture (DFM)	The process of designing parts, components, or products for the ease of manufacturing with a goal of producing a better product at a lower cost.	Minimizes the complexity of manufacturing processes by optimizing the system design.
Design for Manufacture and Assembly (DFMA)	Combines DFM and DFA techniques to create simple, economical products that can be manufactured and assembled easily.	Seeks to reduce total production cost by focusing on the ease of manufacture and assembly during the early design phase.
Design for Reliability (DFR)	The process of designing parts, components, or products with the specific goal of making delivered systems more reliable and available.	More producible systems tend to rely less on overly complex processes, which also tend to make systems more reliable.
Design for Six Sigma (DFSS)	Methodologies focus on the design of new product or processes using the DMADV (Define, Measure, Analyze, Design, and Verify) approach and tools.	Seeks to design products and processes that minimize defects, reduce variation, and optimize processes and product while reducing costs.
Failure Modes and Effects Analysis (FMEA)	A reliability evaluation/design technique that examines potential failure modes within a system and its equipment to determine the effects on equipment and system performance.	A process analysis tool that identifies failure modes, failure effects, failure cause, and failure analysis, all of which affect producibility.
Failure Modes, Effects, and Criticality Analysis (FMECA)	An analysis of a system and the working interrelationships of its elements to determine ways in which failures can occur (failure modes) and the effects of each potential failure on the system element in which it occurs, on other system elements, and on the mission, and the study of the relative mission risk or criticality of all potential failure modes.	A systematic, bottoms-up analysis of the local and system effects of specific failure modes of the equipment. FMECA also evaluates the mission criticality of each failure mode.
Failure Modes and Effects Analysis (FMEA)	A reliability evaluation/design technique that examines potential failure modes within a system	A process analysis tool that identifies failure modes, failure effects, failure

Tool	Description	Producibility Benefits/Application
	and its equipment to determine the effects on equipment and system performance.	cause, and failure analysis, all which impact producibility.
Gage Repeatability and Reproducibility (R&R)	A methodology used to quantify the amount of variation in a production measurement system. Measurement variation consists of two important factors – repeatability and reproducibility. Repeatability is a measure of equipment variation, while reproducibility is a measure of inspector or operator variation.	A robust SPC process requires accurate and precise data to have the greatest impact on product quality, and hence producibility. Gage R&R is a proven method for evaluating the capability of a measurement system.
Process Capability (C_p, C_pk)	Important in manufacturing to ensure that a process produces uniform, defect free product.	Looks at the product to see if manufacturing is producing "good parts" and can be used to predict future behavior.
Process Failure Modes and Effects Analysis	A means for analyzing manufacturing processes to identify potential problems that may induce part defects.	Identify and mitigate failure modes created by the manufacturing process itself. Reduced defects and improved reliability and quality.
Process Performance (P_p, P_pk)	Pp and Ppk studies apply to processes that are stable, in statistical control, and are in production, or used to assess the entire process	Calculated for processes that are stable or unstable, and production is new or has just begun. It is a first important step in assessing and improving producibility on the assembly line.
Producibility Assessment Worksheet	A tool used to quantify and assess the relative merits of candidate manufacturing processes.	Compares the relative benefits of different manufacturing processes to select the most producible ones.
Production Part Approval Process	Provides evidence that all customer engineering requirements are properly understood by the manufacturing organization.	Often used by prime contractors to define their approval process for the acquisition of new or revised parts.
Quality Function Deployment (QFD)	A structured process to translate program needs into system requirements and measurable design targets.	QFD can quantifies the benefits of design features vs. system requirements at all levels of manufacture.
Taguchi Analysis	IA statistical-based mathematical model used to create robust design of experiments. An experimental design is used to identify and exploit the interactions between control and noise factors. Once the significant factors have been identified and their control settings established the resultant product will be optimized by designing quality into the product and processes.	Robust/parameter designs help to support producibility efforts by identifying and reducing variation in a product allowing the product to perform its functions regardless of the various causes of variation (noise factors).
Taguchi Loss Function	A graphical technique to show how an increase in variation from the target value, on key characteristics (KC), can have an exponential impact on cost, reliability, and other production parameters.	A key characteristic has the greatest impact of form, fit, function, and performance compared to all other non-key characteristics. As such, it has the greatest impact on producibility.

APPENDIX B: EXAMPLE PRODUCIBILITY ASSESSMENT WORKSHEET

Producibility assessment is a systems engineering tool to assess design and manufacturing risks. To assess producibility on a product level, both the product and its manufacturing processes should be assessed. Manufacturing processes should be monitored and controlled, through measurement, to ensure they can repeatedly produce accurate, high-quality products, which helps the program meet objectives for limiting process variability to a tolerable range.

Producibility Assessment Worksheets (PAWs) provide a producibility data collection approach to summarize expert opinions on specific producibility topics. The PAW provides input to the Integrated Product Team (IPT) on potential producibility issues and to help the design team to develop courses of action for resolution. The PAW includes numerical values for processes to communicate subject matter expert opinion based on experience and judgment on the product design. It is predicated on subjective data, or information based on the evaluator's experience with similar products. As a best practice, PAWs should be completed on all critical manufacturing processes and should include specific topics such as mechanical systems, electrical systems, and circuit cards, and may include items such as single components, subassemblies, subsystems, and systems.

Because the worksheets are easy to use, the technique or format is flexible to a manufacturer's individual needs and situation. Several example worksheets in different subject areas are included here for reference: mechanical, electrical, management, and source selection. This exercise can be repeated for any other subject area. The specific contents and criteria can be tailored by subject matter experts on the IPT. For further clarification, this section contains a completed version of the "mechanical" worksheet as an example.

PAWs can be used for anything from a single product component to the complete end item. Depending on the scope and applicability, hundreds of PAWs could be used to develop a complete producibility assessment.

EXAMPLE – Mechanical Producibility Assessment Worksheet

The example worksheet provided in Table B-1 is for a power supply assembly required in a new missile program. The example considers three possible manufacturing processes to fabricate the unit where "M1" represents manufacturing process number 1, and "M2" represents manufacturing process number 2:

- M1 – Sheet metal with nuts, bolts, fasteners, and welding operations.
- M2 – Sand castings with secondary machining operations.
- M3 – Investment castings that provide near net shape with minor drilling and tapping operations.

Members of the evaluation team assess each of the three processes against each of the eight categories, by selecting the most appropriate rating in each category and then applying the corresponding numerical value in the Producibility Assessment Value (PAV) table. In this example, the results indicate that M3 (investment casting approach) was rated to have the highest probability of success. The evaluator would present these findings to the program office and other functional disciplines involved in the Power Supply Assembly design. Because of differences of opinion and range of experience, a minimum of three evaluators is recommended for assessment of complex producibility questions.

PAWs may be used past the initial steps. For example, if there are changes in performance or production requirements, these may alter the design complexity, making a different process more favorable than before. Thus, anytime there are significant changes in requirements, a new set of producibility assessments is probably in order.

Table B-1. Mechanical Producibility Assessment Worksheet (Sample)

XYZ (Company Name) _____ Big Missile (Project Name)

Part Name: Power Supply Housing

Supplier: In-house

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
_X_ Production

DTC Goal $90.00

Quantity 8000/yr. 5 yrs.

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1	.5	.3	.9	.7	.3	.9	.3	.7	0.58
M2	.7	.7	.9	.7	.5	.7	.7	.7	0.70
M3	.7	.7	.7	.7	.7	.9	.9	.7	0.75
M4									

PROCEDURE OR PROCESS SELECTION

M1 Sheet metal with nuts, bolts, fasteners & welding operation

M2 Sand castings with secondary machining operations

M3 Investment castings that will provide near net shape with minor secondary operations

M4 _____

MECHANICAL

C1 TECHNICAL 0.9 MINIMAL OR NO CONSEQUENCE 0.7 SMALL REDUCTION IN TECHNICAL PERFORMANCE 0.5 SOME REDUCTION IN TECHNICAL PERFORMANCE 0.3 SIGNIFICANT DEGRADATION IN TECH. PERFORMANCE 0.1 TECHNICAL GOALS ACHIEVEMENT UNLIKELY	C5 DESIGN 0.9 EXISTING / SIMPLE / MFG ENGINEERS INVOLVED 0.7 MINOR REDESIGN FOR ASSEMBLY REQUIRED 0.5 MODERATE REDESIGN / POSSIBLE ASSY PROBLEMS 0.3 COMPLEX DESIGN/SPECIALIZED ASSY EQUP. REQ'D 0.1 STATE OF THE ART / NEEDS R&D / MFG ENG NOT INVOLVED
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-15% IN DTC 0.3 EXCEEDS 16-30% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>31%)	C6 PROCESS 0.9 PROVEN MATURE IN-HOUSE PROCESS 0.7 MINOR EXPERIENCE WITH PROCESS IN-HOUSE 0.5 EXPEREINCE AVAILABLE LOCALLY 0.3 EXPEREINCE AVAILABLE, BUT NOT PROVEN YET 0.1 NO EXPERIENCE, NEEDS R&D
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 INSPECTION 0.9 MINIMAL USE OF STATISTICAL PROCESS CONTROL (SPC) 0.7 MINOR TESTING OR GAGING / FLOOR INSPECTOR AVAILABLE 0.5 CHECK FIXTURES ACCURATE AND REQUIRED AVAILABLE 0.3 REQUIRES EXTENSIVE TESTING AT EVERY WORKSTATION 0.1 100 PERCENT INSPECTION REQ'D / NO SPC
C4 TOOLING 0.9 DEDICATED FIXTURING / FLEXIBLE MFG CENTERS 0.7 SIGNIFICANT FIXTURING / CNC & STD TOOLS 0.5 MODERATE FIXTURES / MANUAL MACHINES 0.3 MINOR FIXTURING/MANUAL MACHINES / PINS & CLAMPS 0.1 SIMPLE FIXTURING / MANUAL CLAMPING	C8 MATERIALS 0.9 READILY AVAILABLE OFF SHELF COMPONENTS 0.7 1-3 MONTH ORDER SOME COMPONENTS 0.5 3-8 MONTH ORDER SOME COMPONENTS 0.3 9-12 MONTH ORDER / SPEC. ORDER COMPONENTS 0.1 12-18 MONTH ORDER

Evaluator _____ Dept _____ Date _____

Table B-2. Mechanical Producibility Assessment Worksheet

_____ _____
(Company Name) (Project Name)

Part Name: _____

Supplier: _____

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
___ Production

DTC Goal _____

Quantity _____

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1									
M2									
M3									
M4									

PROCEDURE OR PROCESS SELECTION

M1 _____ M3 _____
M2 _____ M4 _____

CATEGORY (mechanical, electrical, circuit card, management, source selection)

C1 TECHNICAL 0.9 MINIMAL OR NO CONSEQUENCE 0.7 SMALL REDUCTION IN TECHNICAL PERFORMANCE 0.5 SOME REDUCTION IN TECHNICAL PERFORMANCE 0.3 SIGNIFICANT DEGRADATION IN TECH. PERFORMANCE 0.1 TECHNICAL GOALS ACHIEVEMENT UNLIKELY	C5 DESIGN 0.9 EXISTING / SIMPLE / MFG ENGINEERS INVOLVED 0.7 MINOR REDESIGN FOR ASSEMBLY REQUIRED 0.5 MODERATE REDESIGN / POSSIBLE ASSY PROBLEMS 0.3 COMPLEX DESIGN/SPECIALIZED ASSY EQUP. REQ'D 0.1 STATE OF THE ART / NEEDS R&D / MFG ENG NOT INVOLVED
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-15% IN DTC 0.3 EXCEEDS 16-30% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>31%)	C6 PROCESS 0.9 PROVEN MATURE IN-HOUSE PROCESS 0.7 MINOR EXPERIENCE WITH PROCESS IN-HOUSE 0.5 EXPEREINCE AVAILABLE LOCALLY 0.3 EXPEREINCE AVAILABLE, BUT NOT PROVEN YET 0.1 NO EXPERIENCE, NEEDS R&D
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 INSPECTION 0.9 MINIMAL USE OF STATISTICAL PROCESS CONTROL (SPC) 0.7 MINOR TESTING OR GAGING / FLOOR INSPECTOR AVAILABLE 0.5 CHECK FIXTURES ACCURATE AND REQUIRED AVAILABLE 0.3 REQUIRES EXTENSIVE TESTING AT EVERY WORKSTATION 0.1 100 PERCENT INSPECTION REQ'D / NO SPC
C4 TOOLING 0.9 DEDICATED FIXTURING / FLEXIBLE MFG CENTERS 0.7 SIGNIFICANT FIXTURING / CNC & STD TOOLS 0.5 MODERATE FIXTURES / MANUAL MACHINES 0.3 MINOR FIXTURING/MANUAL MACHINES / PINS & CLAMPS 0.1 SIMPLE FIXTURING / MANUAL CLAMPING	C8 MATERIALS 0.9 READILY AVAILABLE OFF SHELF COMPONENTS 0.7 1-3 MONTH ORDER SOME COMPONENTS 0.5 3-8 MONTH ORDER SOME COMPONENTS 0.3 9-12 MONTH ORDER / SPEC. ORDER COMPONENTS 0.1 12-18 MONTH ORDER

Evaluator _____ Dept _____ Date _____

Table B-3. Source Selection Producibility Assessment Worksheet

_____ _____
(Company Name) (Project Name)

Part Name: _____

Supplier: _____

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
___ Production

DTC Goal _____

Quantity _____

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1									
M2									
M3									
M4									

PROCEDURE OR PROCESS SELECTION

M1 _____ M3 _____
M2 _____ M4 _____

SOURCE SELECTION

C1 TECHNICAL 0.9 CREATIVE – NEW DIRECTIONS 0.7 INNOVATIVE – NEW APPROACH 0.5 ADEQUATE – USUAL APPROACH 0.3 CONVENTIONAL 0.1 TECHNICAL ACHIEVEMENT UNLIKELY	C5 PAST PERFORMANCE 0.9 QUALITY PRODUCTS ON TIME – NO MGT PROBLEMS 0.7 QUALITY PRODUCTS MOST OF THE TIME 0.5 PRODUCTS DELIVERED – MINOR ACCEPTANCE PROBLEMS 0.3 QUALITY DELIVERY PROBLEMS – HIGH MRB ACTIVITY 0.1 SEVER QUALITY PROBLEMS – MANAGEMENT PROBLEMS
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-10% IN DTC 0.3 EXCEEDS 11-15% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>15%)	C6 DATA REQUIREMENTS 0.9 ALL SPECS/CDRLS HAVE BEEN NEGOTIATED 0.7 TAILORING OF ALL SPECS/CDRLS IS ACCOMPLISHED 0.5 ALL SPEC/CDRL COST DRIVERS IDENTIFIED 0.3 ONLY MAJOR SPECS/CDRL COST DRIVERS IDENTIFIED 0.1 NO ID OR TAILORING OF SPECS CDRLS
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 COMPLIANCE WITH REQUIREMENTS 0.9 GREATLY EXCEEDS COMPLIANCE REQUIREMENTS OF PRGM 0.7 EXCEEDS COMPLIANCE REQUIREMENTS 0.5 MEETS MINIMUM COMPLIANCE REQUIREMENTS 0.3 MEETS MOST OF THE MINIMUM REQUIREMENTS 0.1 DOES NOT MEET MINIMUM REQUIREMENTS
C4 TRANSITION PLANNING (TPLAN) 0.9 COMPANY POLICIES FOLLOW DoD 4245.7-M GUIDELINES 0.7 TPLAN STARTED AT CONCEPT PHASE 0.5 TPLAN AFTER DEM/VAL (DSARC PHASE I) 0.3 TPLAN AFTER FSD (DSARC PHASE II) 0.1 NO TRANSITION PLANNING HAS BEEN DONE	C8 UNDERSTANDING OF REQUIREMENTS 0.9 OUTSTANDING UNDERSTANDING OF CUSTOMER RQTS 0.7 GOOD UNDERSTANDING OF MINIMUM REQUIREMENTS 0.5 UNDERSTANDS MINIMUM CUSTOMER REQUIREMENTS 0.3 UNDERSTANDS MOST OF THE MINIMUM REQUIREMENTS 0.1 DOES NOT UNDERSTAND MINIMUM REQUIREMENTS

Evaluator _____ Dept _____ Date _____

Table B-4. Circuit Card Assembly Producibility Assessment Worksheet

_____ _____
(Company Name) (Project Name)

Part Name: _____

Supplier: _____

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1									
M2									
M3									
M4									

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
___ Production

DTC Goal _____

Quantity _____

PROCEDURE OR PROCESS SELECTION

M1 _____ M3 _____

M2 _____ M4 _____

CIRCUIT CARD ASSEMBLY

C1 TECHNICAL 0.9 MINIMAL OR NO CONSEQUENCE 0.7 SMALL REDUCTION IN TECHNICAL PERFORMANCE 0.5 SOME REDUCTION IN TECHNICAL PERFORMANCE 0.3 SIGNIFICANT DEGRADATION IN TECH. PERFORMANCE 0.1 TECHNICAL GOALS ACHIEVEMENT UNLIKELY	C5 DESIGN 0.9 EXISTING STANDARD 2-SIDED PC BOARD 0.7 EXISTING STANDARD MULTILAYER CARD 0.5 MULTILAYER CARD WITH HIGH THERMAL LOADS 0.3 MULTILAYER CARD, HIGH THERMAL, HARD TO WIRE 0.1 HIGHLY COMPLEX UNPROVEN DESIGN
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-15% IN DTC 0.3 EXCEEDS 16-30% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>31%)	C6 RAW CARD FAB PROCESS/ENV. IMPACT 0.9 SIMILAR CARDS IN CURRENT PRODUCTION 0.7 PREVIOUS EXPERIENCE ON SIMILAR CARDS 0.5 PROCESS AVAILABLE – NO EXPERIENCE 0.3 PROCESS DEVELOPMENT REQ'D/POSSIBLE ENV. RISK 0.1 COMPLETELY NEW PROCESS OR HIGH ENV. RISK
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 TESTING/INSPECTION 0.9 CAN BE AUTO TESTED INSPECTED USING STD AUTO EQUIP. 0.7 REQUIRES SPECIAL TEST EQUIPMENT FOR AUTO TEST 0.5 MANUAL TEST/INSPECTION WITH LAB INSTRUMENTS 0.3 TEST INSPECTION REQUIRES ENGINEERING DEVELOPMENT 0.1 TESTING/INSPECTION METHOD UNDEFINED
C4 CARD ASSEMBLY PROCESS 0.9 COMPLETELY ASSEMBLED BY AUTOMATED EQUIPMENT 0.7 SOME MANUAL ASSEMBLY REQUIRED 0.5 COMPLETELY ASSEMBLED MANUALLY 0.3 COMPLEX MANUAL ASSEMBLY / ADJUSTMENTS REQUIRED 0.1 CONTROLLED ENVIRONMENT / COMPLEX MANUAL ASSY	C8 MATERIALS/ELECTRICAL COMPONENTS 0.9 READILY AVAILABLE OFF SHELF COMPONENTS 0.7 1-3 MONTH ORDER SOME COMPONENTS 0.5 3-8 MONTH ORDER SOME COMPONENTS 0.3 9-12 MONTH ORDER / SPEC. ORDER COMPONENTS 0.1 12-18 MONTH ORDER / NEW YHSIC CHIP

Evaluator _____ Dept _____ Date _____

Table B-5. Electrical Producibility Assessment Worksheet

_____ _____
(Company Name) (Project Name)

Part Name: _____

Supplier: _____

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1									
M2									
M3									
M4									

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
___ Production

DTC Goal _____

Quantity _____

PROCEDURE OR PROCESS SELECTION

M1 _____ M3 _____

M2 _____ M4 _____

ELECTRICAL

C1 TECHNICAL 0.9 MINIMAL OR NO CONSEQUENCE 0.7 SMALL REDUCTION IN TECHNICAL PERFORMANCE 0.5 SOME REDUCTION IN TECHNICAL PERFORMANCE 0.3 SIGNIFICANT DEGRADATION IN TECH. PERFORMANCE 0.1 TECHNICAL GOALS ACHIEVEMENT UNLIKELY	C5 DESIGN 0.9 EXISTING SIMPLE 0.7 MINOR REDESIGN 0.5 MODERATE REDESIGN 0.3 TECHNOLOGY AVAILABLE / COMPLEX DESIGN 0.1 STATE OF THE ART / HIGHLY COMPLEX
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-15% IN DTC 0.3 EXCEEDS 16-30% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>31%)	C6 PROCESS 0.9 PROVEN QUALITY PROCESS 0.7 LIMITED PRIOR EXPERIENCE IN-HOUSE 0.5 EXPEREINCE AVAILABLE LOCALLY 0.3 EXPEREINCE AVAILABLE, BUT NOT PROVEN YET 0.1 NO EXPERIENCE, NEEDS R&D
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 INSPECTION 0.9 MINIMAL USE OF STATISTICAL PROCESS CONTROL (SPC) 0.7 MINOR TESTING OR GAGING / FLOOR INSPECTOR AVAILABLE 0.5 CHECK FIXTURES ACCURATE AND REQUIRED AVAILABLE 0.3 REQUIRES EXTENSIVE TESTING AT EVERY WORKSTATION 0.1 100 PERCENT INSPECTION REQ'D / NO SPC
C4 TOOLING 0.9 DEDICATED FIXTURING 0.7 SIGNIFICANT FIXTURING 0.5 MODERATE FIXTURES 0.3 MINOR FIXTURING 0.1 SIMPLE FIXTURING	C8 MATERIALS/ELECTRICAL COMPONENTS 0.9 READILY AVAILABLE OFF SHELF COMPONENTS 0.7 1-3 MONTH ORDER SOME COMPONENTS 0.5 3-8 MONTH ORDER SOME COMPONENTS 0.3 9-12 MONTH ORDER / SPEC. ORDER COMPONENTS 0.1 12-18 MONTH ORDER / NEW VHSIC CHIP

Evaluator _____ Dept _____ Date _____

Table B-6. Management Producibility Assessment Worksheet

_____ _____
(Company Name) (Project Name)

Part Name: _____

Supplier: _____

Program Phase
___ Concept Exploration
___ Demonstration Validation
___ Full Scale Development
___ Production

DTC Goal _____

Quantity _____

	C1	C2	C3	C4	C5	C6	C7	C8	Producibility/Risk Assessment Value (PAV)
M1									
M2									
M3									
M4									

PROCEDURE OR PROCESS SELECTION

M1 _____ M3 _____
M2 _____ M4 _____

MANAGEMENT

C1 TECHNICAL 0.9 MINIMAL OR NO CONSEQUENCE 0.7 SMALL REDUCTION IN TECHNICAL PERFORMANCE 0.5 SOME REDUCTION IN TECHNICAL PERFORMANCE 0.3 SIGNIFICANT DEGRADATION IN TECH. PERFORMANCE 0.1 TECHNICAL GOALS ACHIEVEMENT UNLIKELY	C5 PRODUCIBILITY 0.9 PRODUCIBILITY ASSESSMENTS FROM CONTRACT AWARD 0.7 PRODUCIBILITY STARTED AFTER PDR 0.5 PRODUCIBILITY STARTED AFTER CDR 0.3 PRODUCIBILITY STARTED AFTER FSD 0.1 PRODUCIBILITY NOT CONSIDERED
C2 DESIGN TO COST (DTC) 0.9 BUDGET NOT EXCEEDED 0.7 EXCEEDS 1-5% IN DTC 0.5 EXCEEDS 6-15% IN DTC 0.3 EXCEEDS 16-30% IN DTC 0.1 DTC GOALS CANNOT BE ACHIEVED (>31%)	C6 RISK ASSESSMENT MANAGEMENT 0.9 RISK IS MANAGEABLE AND PREDICTABLE (BLUE) 0.7 RISK IS LOW FOR PROGRAM (GREEN) 0.5 RISK IS MEDIUM FOR PROGRAM (YELLOW) 0.3 RISK IS HIGH FOR PROGRAM (RED) 0.1 NO RISK MANAGEMENT PLAN OR POLICY EXISTS
C3 SCHEDULE 0.9 NEGLIGIBLE IMPACT ON PROGRAM 0.7 MINOR SLIP (<1 MONTH) 0.5 MODERATE SLIP (<3 MONTHS) 0.3 SIGNIFICANT SLIP (3-6 MONTHS) 0.1 STRETCH OUT OF PROGRAM (>6 MONTHS LIKELY)	C7 DATA REQUIREMENTS 0.9 ALL SPECS/CDRLS HAVE BEEN NEGOTIATED INTO CONTRACT 0.7 TAILORING OF ALL SPECS/CDRLS IS ACCOMPLISHED 0.5 AL SPECS/CDRLS COST DRIVERS IDENTIFIED 0.3 ONLY MAJOR SPECS/CDRLS COST DRIVER IDENTIFIED 0.1 NO ID OR TAILORING OF SPECS/CDRLS HAS BEEN DONE
C4 FUNDING 0.9 FUNDING MATCHES PROJECTED BUDGET 0.7 FUNDING ADEQUATE, BUDGET DOES NOT EXCEED 5% 0.5 FUNDING MINIMAL, BUDGET EXCEEDS 15%, OVERRUN LIKELY 0.3 FUNDING SKETCHY, NO COMMITMENT, MAJOR OVERRUN LIKELY 0.1 FUNDING INADEQUATE, ECONOMY UNSTABLE	C8 TRANSITION PLANNING (TPLAN) 0.9 COMPANY POLICIES FOLLOW DoD 4245.7-M GUIDELINES 0.7 TPLAN COMMENC3ES AT CONCEPT PHASE 0.5 TPLAN COMMENCES AFTER DEM/VQAL (DSARC PHASE I) 0.3 TPLAN COMMENCES AFTER FSD (DSARC PHASE II) 0.1 NO TRANSITION PLANNING

Evaluator _____ Dept _____ Date _____

APPENDIX C: GAGE REPEATABILITY AND REPRODUCIBILITY STUDIES

Even when producibility of a product is fully considered, there still exists a degree of variation in the manufacturing process. One of the more effective tools for evaluating measurement variation in the manufacturing process is Gage Repeatability and Reproducibility (Gage R&R).

Gage R&R is a methodology to quantify the amount of variation in the measurement system. Measurement variation consists of two important factors – repeatability and reproducibility. Repeatability is a measure of equipment variation, while reproducibility is a measure of inspector or operator variation (Quality-One 2023).[4] Gage R&R can determine:

- The amount of measurement system variation compared with the process variation.
- The amount of variation in the measurement system that is due to operator influence.
- The measurement system's capability to discriminate between different parts.

A robust SPC process requires accurate and precise data to have the greatest impact on product quality, and hence producibility. Gage R&R is a proven method for evaluating the capability of a measurement system. Gage R&R studies examine the repeatability of equipment and the reproducibility of the appraisers (those who perform measurements). The results of these studies allow manufacturers to predict the percentage or probability of measurement error, and in turn understand the source of the variation (equipment or appraiser).

Sources of Variation in a Gage R&R Study

A Gage R&R study considers four sources of variation, the two major of which are repeatability and reproducibility.

1. Repeatability: Variation in the measurements obtained by one operator measuring the same item repeatedly. This is also called measurement or equipment variation.
2. Reproducibility: Variation of the measurement system caused by differences in the way operators perform the test. It is the variation in the average values obtained by several operators while measuring the same item and is sometimes called the appraiser variation.

   The combined repeatability and reproducibility make up the Gage R&R variability.

3. Part variation: A measure of how much the parts vary and should be representative of what occurs in production—this assumes a measurement system is being used to control the process.

4. Total variation: A measure of the variation in all the results. The relationship between the total, part and measurement system variation is given by the equation below:

$$\sigma_t^2 = \sigma_p^2 + \sigma_{ms}^2$$

[4] https://quality-one.com/grr/#SnippetTab

Where the subscripts represent the source (t = total, p = part, and ms = measurement system). Note that this equation is sum of variances (a variance is the square of a standard deviation (σ).

Gage R&R Methodologies

There are several ways to analyze a Gage R&R study. The most common methods are (SPC 2019)[5]:

- Average and Range Method.
- ANOVA Method.
- EMP (Evaluating the Measurement Process) Method.

Average and Range Gage R&R Analysis

The average and range method forms subgroups based on each operator-part combination (e.g., one subgroup is A-1 for operator A and part 1). Subgroup averages and ranges are calculated. First, each operator's average and range are calculated, then the average range for all operators is then found. To find the repeatability (termed EV for equipment variation), the average range (termed R) is multiplied by a constant, K1, which depends on the number of trials. A table of K-values is available in the Measurement Systems Analysis Manual (AIAG 2010)[6]. The equation is expressed as:

$$EV = R(K_1)$$

The value of EV does not represent a variance. It represents a standard deviation. The range in operator averages is then calculated. This is called $\bar{\bar{X}}_{DIFF}$. This value is used in the following equation to find the reproducibility or the appraiser variability (AV).

$$AV = \sqrt{(\bar{X}_{DIFF} * K_2)^2 - (EV)^2/nr}$$

K_2 is a constant that depends on the number of operators, n is the number of parts, and r is the number of trials. The Gage R&R value is then found by combining the EV and AV results using the following equation:

$$Gage\ R\&R = \sqrt{EV^2 + AV^2}$$

The part variation (PV) is found by determining the range in part values (Rp) and multiplying this range by a constant (K3) that depends on the number of parts:

$$PV = Rp(K_3)$$

[5] https://www.spcforexcel.com/knowledge/measurement-systems-analysis/five-common-mistakes-gagerr#:~:text=There%20are%20several%20ways%20to%20analyze

[6] Measurement Systems Analysis Manual, 4th edition, AIAG, 2010

Finally, the total variation (TV) is determined by the following equation:

$$TV = \sqrt{(Gage\ R\&R)^2 + PV^2}$$

ANOVA Gage R&R Analysis

Analysis of variance (ANOVA) is a technique that identifies and quantifies the sources of variation. ANOVA compares the variation in part and operator results to the repeatability of the test method. ANOVAs are typically performed by software programs because of their complexity. A typical ANOVA output might look like the example below (Table C-1).

Table C-1. Example of ANOVA Gage R&R Analysis

Source	df	SS	MS	F	p Value
Part	9	88.362	9.818	245.614	0
Operator	2	3.167	1.584	39.617	0
Repeatability	78	3.118	0.04		
Total	89	94.647			

The first column is the source of variability. Operator here represents the reproducibility. The second column (df) is the degrees of freedom associated with the source of variation. This is a measure of the amount of data present. The third column is the sum of squares (SS). This is a measure of the variation in the data for that source. The fourth column is the mean square (MS) associated with the source of variation. The mean square is the estimate of the variance for that source of variability (not necessarily by itself) based on the amount of data available (the degrees of freedom). So, the mean square is the sum of squares divided by the degrees of freedom.

The mean square information is used to estimate the variance of each source of variation – this is the key to analyzing the Gage R&R results. The fifth column is the F value. This statistic is calculated to determine if the source of variability is statistically significant. It is based on the ratio of two variances (or mean squares in this case). The last column is the p value; a value of $\leq$ 0.05 is considered significant. So, both the parts and operator have a significant effect on the results. With ANOVA, one determines the percent of the total variance (not standard deviation) due to each source. The repeatability variance is simply the mean square of the repeatability source of variation.

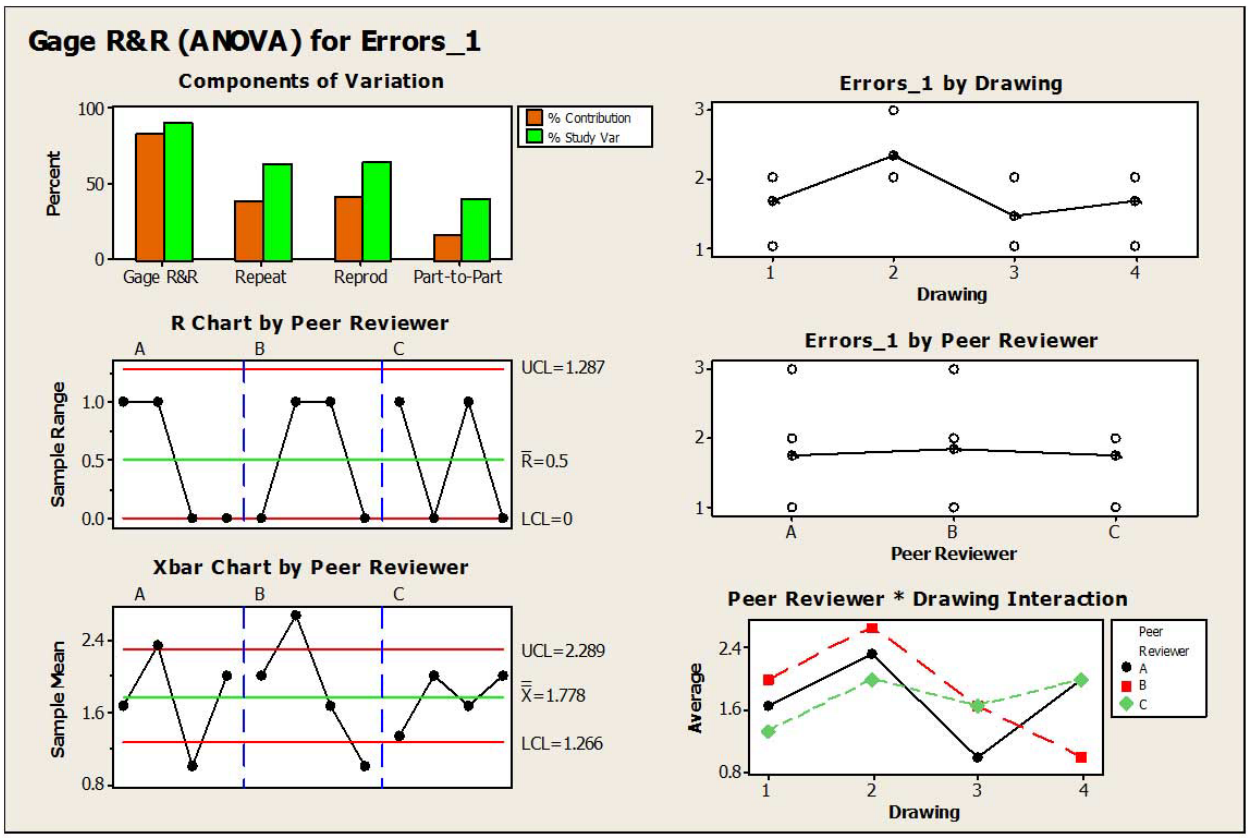


Figure C-1. Sample ANOVA Charts

EMP Gage R&R Analysis

The Evaluating the Measurement Process (EMP) methodology is similar to the ANOVA method in that it determines the variances due to the different sources of variation and determines the percent contribution from each source. Like the Average and Range method, it uses subgroups of data to determine the variance due to the various sources of variation. Unlike ANOVA, it does not consider the operator-part interaction. The approach includes the use of control charts. A range chart is made based on the subgroups composed of each operator-part combination. If the range chart is in statistical control, the repeatability can be estimated from the average range:

$$\sigma_{pe}{}^2 = \left(\frac{\bar{R}}{d_2}\right)^2$$

where d_2 is a control chart constant that depends on subgroup size (the number of trials). The range of operator averages is used to find the reproducibility using the following:

$$\sigma_0{}^2 = \left(\frac{R_0}{d_2^*}\right)^2 - \left(\frac{o}{(n)(o)(p)}\right)\sigma_{pe}^2$$

where R_0 is the range of operator averages, d^*_2 is a bias correction factor that depends on the number of operators, n = number of trials, o = number of operators, and p = number of parts. The combined R&R variance is the sum of the repeatability variance and the reproducibility variance:

$$\sigma_e^2 = \sigma_{pe}^2 + \sigma_o^2$$

EMP Gauge R&R Results

Component	Std Dev	Variance Component	% of Total	20 40 60 80
Gauge R&R	0.28512278	0.08129500	38.7	
Repeatability	0.28512278	0.08129500	38.7	
Reproducibility	0.00000000	0.00000000	0.0	
Product Variation	0.34202592	0.11698173	55.7	
Interaction Variation	0.10899541	0.01188000	5.7	
Total Variation	0.45842854	0.21015673	100.0	

Figure C-2. Sample Output of EMP Gage R&R Analysis

The EMP approach uses a completely different method. It classifies each test method as a First, Second, Third, or Fourth-Class monitor based on the intraclass correlation coefficient (r), which is the ratio of the part variance to the total variance:

$$\rho = \frac{\sigma_p^2}{\sigma_x^2} = \frac{\sigma_x^2 - \sigma_e^2}{\sigma_x^2} = 1 - \frac{\sigma_e^2}{\sigma_x^2}$$

The subscripts are as follows: x = total variance, p = part variance, e = measurement system variance. So, the intraclass correlation coefficient is also equal to one minus the percent variance due to the measurement system (the percent R&R). AIAG guidelines for acceptability suggest how the results be interpreted (Table C-2).

Table C-2. Interpreting the EMP Results

ρ	Type of Monitor	Reduction of Process Signal	Chance of Detecting ± 3 Std. Error Shift	Ability to Track Process Improvements	% R&R/AIAG Guideline
0.8 to 1.0	First Class	Less than 10%	More than 99% with Rule 1	Up to Cp80	0 to 20%/Acceptable to Marginal
0.5 to 0.8	Second Class	From 10% to 30%	More than 88% with Rule 1	Up to Cp50	20 to 50%/Marginal to Unacceptable
0.2 to 0.5	Third Class	From 30% to 55%	More than 91% with Rules 1, 2, 3 and 4	Up to Cp20	50% to 80%/Unacceptable
0.0 to 0.2	Fourth Class	More than 55%	Rapidly Vanishing	Unable to Track	80% to 100%/Unacceptable

Table adapted from EMP III Evaluating the Measurement System, by Donald J. Wheeler, 2006 SPC Press.

Best Practices for Producibility

In performing Gage R&R studies, the ANOVA or EMP methodologies are preferable to the Average and Range method for two reasons. First, the method depends largely on calculations by practitioners which may contribute variability through calculation errors. Second, variations are measured in standard deviations, and not variances. This is important because standard deviations are not additive, thus the percent variations do not add up to 100 percent. In terms of producibility, the Average and Range method is less accurate, making it more difficult to run a production operation at optimum producibility.

Alternately, ANOVA and EMP equations are based on variances, which are additive, and thus can be used to interpret the relative contributions of each source of variance. EMP is a methodology that originates out of AIAG; thus, analysts would need to acquire the appropriate materials from AIAG to perform them. On the other hand, ANOVA is a well-established and widely used methodology for which many software packages exist.

In addition to analysis, recommended best practices for measurement include Feldman (2023):

- Select people for the study that do the process. Do not add sources of variation by using participants who are not experienced or do not perform the process as a natural part of their job.
- Remove any bias by having the participants measure the objects in random order. Randomize the objects so they must measure the object rather than being able to rely on memory.
- The project team should conduct the study as part of the regular previously performed process. Run the process under “normal” conditions. Do not contaminate the study with any extraneous variation such as change in environmental factors (e.g., change in temperature).

This page is intentionally blank.

APPENDIX D: MANUFACTURING AND QUALITY ASSURANCE RFP INPUT

Manufacturing and Quality Assurance Request for Proposal Input

Contents

Introduction

This document provides examples for Manufacturing and Quality Request for Proposal (RFP) inputs, including the Statement of Work (SOW), Sections L and M for competitive acquisitions, and Federal Acquisition Regulation (FAR)/Defense Federal Acquisition Regulation Supplement (DFARS) requirements.

The Core SOW requirements should be used on all Acquisition Category (ACAT) I programs. They may be used on other programs but should be tailored as needed to match the scope and needs of each program. For all the requirements and other inputs in this guide, program team with input from manufacturing and quality specialist should conduct specific tailoring to ensure requirements are appropriate to meeting the unique needs and circumstances of each program.

If possible, developing contractual requirements should be a collaborative process between the government program office and the prime contractor.

Data Item Descriptions (DIDs):

- Prior to using a DID, ensure the most current version is being referenced.
- Use caution when calling out DIDs: Some requirements in the SOW do not have DIDs that directly correspond to them. In those cases, the closest, related DID is suggested. In other cases, some DIDs may be significantly outdated. They were provided to serve as a potential starting point and may need to be tailored. These will be discussed in each section, if applicable.

Manufacturing and Quality RFP Guide Summary Applicability Matrix

The following table is provided for general guidance only. Specific determinations of program and contract applicability should be made on a case-by-case basis.

All requirements are applicable to land, sea, air, and space-based systems. The only exception is for Aviation Critical Safety Items, which are applicable only to air and space systems.

Where checkmarks are shown that requirement should be considered for inclusion in a SOW. Requirements may still be tailored to meet program needs.

Manufacturing and Quality Input to RFP

Manufacturing/Quality RFP Inputs	MSA	TMRR	EMD	P&D	O&S	Design Change	NDI/COTS
Core SOW Inputs							
Manufacturing Management Program		✓	✓	✓	✓	✓	
Quality Management System Requirements		✓	✓	✓	✓	✓	✓
Manufacturing Readiness Levels and Assessments (MRLs)	✓	✓	✓	✓	✓	✓	✓
Quality and Manufacturing Metrics		✓	✓	✓	✓	✓	✓
Counterfeit Parts Prevention		✓	✓	✓	✓	✓	✓
First Article Inspections/First Article Tests			✓	✓	✓	✓	✓
GIDEP Participation			✓	✓	✓	✓	
Production Readiness Review			✓	✓		✓	✓
Other SOW requirements to consider							
Aviation Critical Safety Items		✓	✓	✓	✓	✓	
Manufacturing Modeling and Simulation		✓	✓	✓	✓	✓	
Calibration			✓	✓	✓	✓	
Configuration Management		✓	✓	✓	✓	✓	
Risk Management		✓	✓	✓	✓	✓	
Parts, Materials, and Processes Control Program		✓	✓	✓	✓	✓	
Environmental Stress Screening		✓	✓	✓	✓	✓	
Key Characteristics and Variation Reduction		✓	✓	✓	✓	✓	
Advanced Product Quality Planning (APQP) & Production Part Approval Process (PPAP)			✓	✓	✓	✓	

1. Core SOW Inputs

1.1. Manufacturing Management Program

The contractor shall establish and maintain a Manufacturing Management Program that meets the requirements of SAE AS6500A and flow this requirement down to major/critical suppliers. The contractor shall document this program as part of their Manufacturing Plan. The contractor shall include its plans for Production Readiness Reviews (PRRs) and Manufacturing Readiness Level (MRL) Assessments in the Manufacturing Plan.

Suggested Data Item Description (DID):

- DI-MGMT-81889B, Manufacturing Plan

Guidance:

1. Major and critical suppliers are defined in AS6500A:

Critical Supplier: A contractor whose performance could seriously jeopardize the successful achievement of a program's cost, schedule, technical, or supportability requirements if not satisfactorily managed (e.g., a sole source supplier or supplier of critical parts, strategic and critical materials, or unique or special processes.)

Major Supplier: A supplier, distributor, vendor, or firm that furnishes supplies or services to or for the prime contractor whose total costs are a significant portion of the total purchased value for the program.

2. While the requirement for a manufacturing management system is applicable during the TMRR phase, it may be too early to require a deliverable manufacturing plan.

3. The DID for a Manufacturing Plan, DI-MGMT-81889B, was updated to be consistent with AS6500A.

1.2. Quality Management System Requirements

The contractor shall establish and maintain a Quality Management System (QMS) that meets the requirements of AS9100. The quality system shall ensure delivery of product that complies with all technical requirements. The Contractor shall document how the QMS is implemented with any unique requirements within the Quality Assurance Program Plan. Major/critical suppliers and suppliers with design authority shall be required to establish and maintain a Quality Management System (QMS) in accordance with requirements of AS9100. Suppliers without design authority shall be compliant to SAE AS9003, Inspection and Test Quality System, as a minimum.

Suggested DID:

- DI-QCIC-81794A, Quality Assurance Program Plan, contractor format acceptable

Guidance:

1. AS9100 is the preferred requirement for a Quality Management System for ACAT I programs in Aviation, Space, and Defense Organizations. The Federal Acquisition Regulation, Part 46, also recognizes overarching quality management system standards such as ISO 9001, ASQ/ANSI E4; ASME NQA-1, SAE AS9003, and ISO/TS 16949. If applying any of these other standards, ensure they are appropriate to the complexity and criticality of the product.

2. The most recent version of AS9100 (or equivalent standard) shall be specified.

3. While the requirement for a quality management system is applicable during the TMRR phase, it may be too early to require a deliverable quality plan.

1.3. Manufacturing Readiness Levels and Assessments (MRLs)

The contractor shall conduct assessments of manufacturing readiness in accordance with AS6500A and use the definitions, criteria, and processes defined in the Manufacturing Readiness Level Deskbook as a guide. Assessments will be conducted at the locations and frequencies specified in {*Program office to include appropriate RFP reference location*}. They will be led by the government program office at the prime contractor's facilities. The prime contractor shall lead the assessments at suppliers and include government participants. The selection of supplier assessments should be determined by the government and prime contractor using the MRL Deskbook, Section 4.3 as a guide. The contractor shall develop and implement Manufacturing Maturation Plans or their equivalent for criteria in which the MRL is lower than the target MRL. The contractor shall monitor and provide status at all program reviews for in-house and supplier MRLs and shall re-assess MRLs in areas for which design, process, source of supply, or facility location changes have occurred that could impact the MRL.

Suggested DIDs:

- DI-SESS-81974, Assessment of Manufacturing Risk and Readiness
- DI-ADMIN-81249B, Conference Agendas
- DI-ADMIN-81250B, Conference Minutes
- DI-MISC-80508B, Technical Report – Study/Services

Guidance:

1. Ensure DIDs are current and appropriate.

1.4. Quality and Manufacturing Metrics

In accordance with AS6500A, the contractor shall maintain a manufacturing surveillance process. The contractor shall submit quality and manufacturing metrics at the agreed upon frequency that report the contractor's and major/critical suppliers' performance and progress. Metrics shall include cost, schedule, and quality metrics to monitor the effectiveness of the contractor's manufacturing, quality, and supplier management programs. Metrics shall be

presented at design, technical, and program management reviews. The contractor shall provide on-line access, between reporting intervals, of the data collected for these metrics.

Suggested DIDs:

- DI-QCIC-82323, Manufacturing and Quality Assurance Status Report

Guidance:

1. Tailor the list of metrics in the DID to meet your specific program needs.

2. On-line access to contractor metrics may be desired, but not feasible. Discuss this with the prime contractor before including this as a requirement.

1.5. Counterfeit Parts Prevention

The contractor shall develop and implement a Counterfeit Parts Prevention (CPP) program in compliance with SAE AS5553 and AS6174 to prevent the inclusion of counterfeit parts or parts embedded with malicious logic into products intended for sale to the Government. These requirements shall be flowed to suppliers to ensure requirements are met. As part of CPP, the contractor shall make available to the government Certificates of Conformance (CoC) as well as supply chain traceability for all electronic part purchases.

Suggested DID:

- DI-MISC-81832, Counterfeit Prevention Plan

Guidance:

1. The RFP could request the elements of DI-MISC-81832 be included in the contractor's Program Protection Implementation Plan (PPIP), DI-ADMN-81306. Another good reference source is SAE-AS6081; Parts, Electronic, Fraudulent/Counterfeit: Avoidance, Detection, Mitigation, and Disposition.

2. The DID may be significantly out of date. Review for appropriateness prior to use.

1.6. First Article Inspections (FAI)/First Article Tests (FAT)

The contractor shall establish an FAI/FAT process and perform FAIs/FATs on new and modified product in accordance with AS9102, "Aerospace First Article Inspection Requirement." First article inspections shall be conducted on new products representative of the first production run and when changes occur that invalidate the original results (e.g., engineering changes, manufacturing process changes, tooling changes). The contractor shall notify the Government program office, and designated representative(s) of first article inspection events to allow for participation. An FAI/FAT report shall be generated for each product as evidence that the engineering requirements have been met.

Suggested DIDs:

- DI-NDTI-81307A, First Article Qualification Test Plan and Procedures
- DI-NDTI-80809, Test/Inspection Report

Guidance:

1. The DIDs may be out of date or not related exactly to the SOW requirement. Review for appropriateness prior to use.

2. Applicability to O&S phase is based on new designs, suppliers, or other changes.

1.7. Government Industry Data Exchange Program (GIDEP) Participation

The contractor shall implement procedures and processes for their participation in GIDEP, including the submission of alerts/advisories to GIDEP when warranted. The processes and procedures shall describe how the contractor (a) receives alerts and advisories from GIDEP and other sources, (b) determines any impact to their product design and already manufactured hardware, (c) implements corrective action procedures when design and/or produced hardware are affected, and (d) includes supplier participation.

Suggested DID:

- DI-QCIC-80125B, Government Industry Data Exchange Program (GIDEP) Alert/Safe-Alert Report
- DI-QCIC-80126B, Government Industry Data Exchange Program (GIDEP) Alert Response

1.8. Production Readiness Review (PRR)

The contractor shall perform PRRs in support of the Milestone C Full Rate Production Decision in accordance with IEEE 15288.2. These requirements shall be flowed to the contractor's major and critical suppliers.

Suggested DIDs:

- DI-ADMIN-81249B, Conference Agendas
- DI-ADMIN-81250B, Conference Minutes
- DI-MISC-80508B, Technical Report – Study/Services

Guidance:

1. The requirement for a PRR is a Core requirement for contracts that will result in a Milestone C or FRP Decision

2. Ensure deliverable plans, minutes, etc., are not already required in another section of the SOW for technical reviews and audits. Ensure DIDs are compatible with IEEE 15288.2 requirements, if imposed.

2. Other SOW Requirements to Consider

2.1. Aviation Critical Safety Items (CSIs)

The contractor shall establish and maintain an auditable program for managing critical safety items (CSI) in accordance with SAE AS9100, SAE AS9017, and SAE AS9103. The contractor shall develop a list of recommended CSIs per SAE AS9017 for government approval. The Contractor shall establish and maintain an auditable program for variation management of Key or Critical Characteristics in accordance with SAE AS9100, and SAE AS 9103 requirements. The contractor shall flow requirements to the lowest level of the supply chain.

Suggested DIDs:

- DI-SAFT-81932, Critical Safety Item (CSI) / Critical Application Item (CAI) List
- DI-SAFT-80970A, Critical Safety Item, Characteristic and Critical Defect Report

Guidance:

The DIDs may be out of date. Review for appropriateness prior to use.

2.2. Manufacturing Modeling and Simulation

The contractor shall analyze manufacturing processes using Modeling & Simulation (M&S) techniques to identify potential bottlenecks or constraints, and confirm the achievability of planned cycle times, etc., and provide the government access to the model and data. The model should use commercially available simulation software used to evaluate scenarios and impacts of process variabilities, plant optimizations, production rate changes, capacity planning, and estimate required quantities of tooling, personnel, and inventory. The contractor shall update the production simulation model for facility modifications and other significant changes.

Suggested DID:

DI-MISC-80508B, Technical Report – Study/Services

Guidance:

1. While AS6500A requires the use of Modeling & Simulation, this additional requirement should be imposed if the government program office needs to obtain the contractor's manufacturing model(s) as a deliverable item. This would enable the program office to conduct independent capacity and schedule assessments and to better identify risks independently from the contractor.

2. The DID may be out of date. Review for appropriateness prior to use.

2.3. Calibration

The contractor shall maintain a calibration system in accordance with ANSI/NCSL Z540.3. The calibration system shall control the accuracy of measuring and test equipment, and measurement standards, used to ensure that products delivered to the Government comply with all contract technical specifications. The calibration system shall prevent inaccuracy by ready detection of deficiencies and timely positive action for their correction. Contractors who operate and maintain calibration laboratories or subcontract to outside calibration laboratories shall ensure compliance with requirements of ISO/IEC 17025:2017, General Requirements for the Competence of Testing and Calibration Laboratories.

2.4. Configuration Management

The contractor shall establish, document, and maintain a Configuration Management (CM) system for control of all configuration documentation, physical media, and physical parts representing or comprising the product, which includes all hardware, software, and firmware. The contractor's CM system shall consist of these elements:

a. CM and planning.
b. Configuration identification.
c. Configuration change management.
d. Configuration status accounting.
e. Configuration audit.
f. CM of digital data.

The contractor may use MIL-HDBK-61B as additional guidance for CM.

Suggested DID:

- DI-SESS-80858, Supplier's Configuration Management Plan
- DI-SESS-80640, Request for Variance
- DI-SESS-80639, Engineering Change Proposal
- DI-SESS-81253, Configuration Status Accounting (CSA) Information

Guidance:

1. Applicability during TMRR should be determined on a case-by-case basis. Consult Configuration Management Subject Matter Experts for guidance.

2.5. Risk Management

The contractor shall establish and maintain a risk management program to continuously identify, analyze, mitigate, monitor, and report systems engineering process, product, technology, cost, schedule, and other program risks. Risk management process results shall be used for continual improvement and risk reduction. Program risks must be assessed and managed at the appropriate

level. The contractor shall establish and maintain risk management programs consistent with the DoD Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs.

2.6. Parts, Materials, and Processes Control Program

The contractor shall establish, document, and maintain a Parts, Materials, and Processes Control Program (PMPCP) to ensure selection and use of parts, devices, and materials, including commercial and non-developmental items, meet specified performance, quality, reliability, safety, supportability, and configuration management requirements throughout the life cycle of the system. The program shall include provisions for mitigating the impact of counterfeit parts and parts obsolescence on product integrity.

The contractor shall flow down applicable PMPCP requirements to applicable lower-tier suppliers.

The contractor may use SD-22, MDA-QS-003-PMAP, MIL-STD-11991B, or SMC Standard SMC-S-009 as additional guidance for control of Parts, Materials, and Processes.

Suggested DID:

- DI-MGMT-81949, DMSMS Implementation Plan
- DI-STDZ-81993, Parts, Materials, and Processes Management Plan.

For additional guidance, refer to SD-26, DMSMS and Parts Management Contracting Guide.

2.7. Environmental Stress Screening

The contractor shall implement an Environmental Stress Screening (ESS) program to surface defects by stressing the item without degrading its inherent reliability. Environmental stresses (i.e., thermal cycling and random vibration) may be applied in sequence or in combination, with the intent of stimulating hardware defects. The ESS program should not be used to simulate an operational environment. Results of ESS shall be used to continually improve manufacturing processes. The contractor may use MIL-HDBK-344 as additional guidance for planning, controlling, and measuring the effectiveness of the ESS program.

Guidance:

1. Imposing ESS requirements should be a joint determination by engineering, manufacturing, Quality, and Reliability functional experts. Consider using ESS on major and critical suppliers of electrical, electronic, electro-optical, electromechanical, or electrochemical components in demonstration & validation, engineering & manufacturing development and production phases.

2.8. Key Characteristics and Variation Reduction

The contractor shall identify Key Characteristics and implement a Variation Reduction program in accordance with AS9103.

2.9. Advanced Product Quality Planning (APQP) & Production Part Approval Process (PPAP)

The contractor shall implement APQP and PPAP programs in accordance with AS9145.

2.10. Additional SOW Considerations

This section includes producibility related SOW considerations derived from MIL-STD-1528A, Manufacturing Management Program, and input from DoD M&Q practitioners. These are provided for reference and require tailoring based on program life cycle phase considerations and specific program requirements and risks.

2.10.1 Design analysis for manufacturing

The contractor's manufacturing management program shall provide for design analysis resulting in a design which will be manufactured efficiently. Design review shall assure consideration of the objectives of manufacturing management with other design trade-offs. The following elements shall be incorporated in the review process.

2.10.2 Producibility analysis

The contractor shall develop a comprehensive, well-defined producibility analysis effort as a prerequisite to entering EMD. The contractor shall develop a producibility element of the manufacturing plans, which:

a. delineates the responsibilities of all disciplines and functions involved in producibility analysis.
b. provides procedures and criteria for selecting candidate items for producibility analysis.
c. prescribes techniques for producibility analyses.
d. identifies criteria used in producibility analysis.

Adequate producibility of the design shall be addressed at system requirement review, system design review, preliminary design review, critical design review and production readiness review. The EMD development phase shall include provisions to attain producibility of the design using cost-effective manufacturing methods and processes. Resource requirements for producibility analysis, long lead procurements and limited production shall be identified, and risks addressed. The contractor shall confirm the capability to meet production unit cost, schedule, and surge goals through an industrial resource analysis at the prime and critical subcontract locations. Included in this analysis shall be the impact of ongoing manufacturing technology, producibility and industrial modernization incentives programs. Producibility efforts shall continue through the full rate production phase.

2.10.3 Producibility Criteria

Producibility criteria based on all design characteristics shall develop and documented during the earliest program phase and shall be updated iteratively as the design is developed. Design

conformance with the criteria shall be addressed in the manufacturing feasibility and capability assessments at each major design review.

2.10.4 Design Analysis

Manufacturing, process, and method analysis of each major element of the design shall be conducted during the design process. Analysis shall be documented and traceable. This analysis shall consider surge and mobilization support needs and shall address:

a. Material selection: critical and strategic material conservation, avoidance of dependence on foreign sources, constraints on surge and - mobilization responsiveness, and standardization of materials and components, and material lead time.
b. Production tooling, special tooling, and test equipment concepts.
c. New or unique processes.
d. Sequencing of assembly events, ease of assembly.
e. Test and inspection instrumentation concepts.
f. Manufacturing and test software.
g. Tooling and facility utilization.
h. Work methods to be used in rate production.
i. Production quantity and rate.
j. Process yield and stability and the impact of process variability on product quality.

This analysis will be submitted as specified in the contract prior to each formal design review. Analysis shall identify the most economical ways to manufacture the product at the required rate and shall indicate capability and capacity factors related to the design.

2.10.5 Manufacturing Integration in the Design Process

Manufacturing and quality engineering shall be integrated into the contractor's system engineering processes. Manufacturing and quality engineering specialist shall have a formal, traceable part in the engineering decisions-making process relating to hardware design and shall act as the formal manufacturing management interface with the system engineering entity. System engineering practice shall assure application of producibility criteria developed as part of the manufacturing feasibility and capability estimate. Factors listed in paragraph 5.2.3 shall be applied iteratively during design development as an element of the manufacturing engineering contribution to the system engineering process.

2.10.6 Production Readiness Review (PRR)

The contractor shall conduct PRRs on key systems, subsystems and suppliers as agreed by the government. PRRs may be conducted incrementally. Each review is conducted determine that significant manufacturing problems have been resolved, or that plan for their resolution acceptable to the government has been developed. The contractor shall provide necessary resources to support the PRR. Contractor conducting PRRs at subcontractor facilities will afford government representatives the opportunity to attend as observers. Prime contractors are

responsible for assuring government program management that subcontractors are satisfactorily preparing for production whether or not formal subcontractor PRRs are conducted.

2.10.7 Manufacturing Feasibility and Capability Assessments

The contractor shall make and formally document a manufacturing feasibility and capability assessment(s) in the conceptual phase, concurrently with the overall program feasibility and risk analysis. Assessments shall be made for each competing design alternative under consideration at the time of the assessment.

Manufacturing feasibility and capacity assessment(s)shall analyze manufacturing resources needed. The assessments shall:

a. Identify required production processes and manufacturing techniques not currently available, and the risks associated with advance development, the probability of meeting the need date, and possible contingency actions.
b. Identify potential impact of critical and long lead time material and production equipment, the probability of meeting the need date, and possible contingency action.
c. Provide production feasibility, cost, and schedule impact analyses to support trade-offs among alternatives.
d. Provide cost and production schedule estimates to support management reviews.
e. Determine an efficient rate of production and rate acceleration curve (preliminary during the Technology Maturation and Risk Reduction Phase; final during Engineering and Manufacturing Development phase).
f. Make recommendations for anticipated production testing and demonstration efforts—including specific requirements for production run demonstration using production tooling, test equipment, and manufacturing equipment.
g. Develop methods of conserving critical and strategic materials and reducing reliance on foreign sources and reducing reliance on foreign sources.
h. Identify potential production bottlenecks and limiting factors to rate production.
i. Be documented and reported for government approval.

2.10.8 Non-Conforming Material

The contractor shall utilize a documented system for evaluating and disposition of non-conforming material. This system shall be used for tracking, analyzing to determine root cause, and assuring effective preventative/corrective action implementation. The contractor shall ensure that all products meet specified contractual requirements. Installation or use of non-conforming products without specific Government authorization is not permitted. Non-conformances shall not be given a disposition of “use as is’ or “repair” through contractor action without Government approval. Rework to print is acceptable. The contractor shall maintain a procedure to control the identification, documentation, evaluation, disposition, and segregation requirements of non-conforming products. The Government shall be notified of any non-conforming products via the Material Review Board (MRB) or Request for Deviation (RFD) process. The Contractor shall notify the Procuring Contracting Officer (PCO) immediately of any discovered non-conformances that may exist in previously delivered product. Notification

shall include a description of the suspected nonconformance, potential risk or product impact, contract number, Part Number, National Stock Number (NSN), affected serial numbers, or lot numbers, when applicable.

2.10.9 Quality Program Plan

The contractor shall prepare, or update if already prepared, a quality program plan (QPP) IAW DI-QCIC-81722. The QPP shall describe the methodology used throughout all phases of the program (development, fabrication, test, delivery, and post-delivery support) to meet the quality requirements for this program. This plan shall maximize the use of existing policies and procedures to the extent that they meet the quality requirements of this document and shall contain a listing of the procedures that are used to satisfy the Quality Assurance (QA) requirements of the program.

2.10.10 Product Acceptance System

The contractor shall plan, develop, implement, and/or maintain a product acceptance system that demonstrates compliance to the technical and contractual requirements. The product acceptance system shall address system and subsystem component requirement verification, in-process inspection, and final acceptance testing at all levels, including lower tier subcontractors and suppliers. The product acceptance system shall identify all end items that require individual ATPs based on the criticality of the item. All items shall successfully complete acceptance testing prior to delivery to the Government and prior to use of the item in any test activity. The product acceptance system shall be approved by the Government. End item acceptance test procedures (ATPs) and equipment, including Special Inspection Equipment (SIE) and Special Test Equipment (STE), shall be validated prior to use for delivery of hardware. The Government shall be given the opportunity to participate in the validation. The contractor shall prepare validation plans IAW DI-MISC-80759. System level and end item ATPs shall be prepared IAW DI-NDTI-80603. Changes to acceptance test procedures and/or associated equipment, vendor changes, line relocations, production disruptions, or downtime exceeding 12 months shall be reviewed by the Government for determination of re-validation requirements.

2.10.11 Subcontractor/Supplier Quality Management

Procedures and policies for managing Subcontractor/Supplier quality shall be documented. The subcontractor/supplier quality management plan shall identify processes for selecting, qualifying and managing subcontractors/suppliers, managing product and processes, flowing applicable quality requirements to subcontractors/suppliers, assessing subcontractor/supplier’s capabilities, verifying compliance of subcontractors/suppliers and establishing metrics for continuously monitoring and rating supplier quality performance. The subcontractor/supplier quality management plan shall address product acceptance requirements for suppliers and emphasis shall be placed on product verification at the supplier level to reduce the amount of incoming receiving inspection and test. The contractor shall identify key features, characteristics and performance requirements that shall be verified at the component acceptance test level.

2.10.12 Gauge Repeatability and Reproducibility (Gauge R&R)

Gauge R&R test variability qualification shall be addressed in the validation plan and demonstrated for the following conditions: (a) Where test stations are used for acceptance purposes – including multiple pieces of equipment and locations (i.e. at each site, if located at more than one); (b) Where test equipment is physically moved to another location - including within the same facility; (c) Where SIE configuration, software, or hardware changes are implemented. A precision-to-tolerance (P/T) ratio of .25 maximum is allowed for state of the art/difficult to measure parameters and should be avoided if possible. Contractor justification and government approval is required for P/T ratios greater than .25. A P/T ratio of .1 or less is the desired limit. Operator variability precautions should be observed where possible. Variability tests shall be conducted on multiple parts. A minimum of two tests shall be conducted on two different serial numbers of the same part. 10 is the desirable number of tests and parts.

2.10.13 Process Management

The Contractor shall prepare and implement a process management plan IAW DI-MGMT-81117. The management plan shall address the contractor's and the subcontractor's/supplier's facilities methodology for process validations, establishing process capability, variability reduction, and the use of Statistical Process Control (SPC).

2.10.14 Process Validation

The process validation shall verify that all new or existing manufacturing processes and technologies produce hardware representative of the planned production configuration that is specified in the contract. The Contractor shall validate all new manufacturing processes/technologies and any existing processes/technologies that require changes IAW the validation plan. The Government may participate in these process validations through the IPT process.

2.10.15 Process Capability

The contractor shall prepare and update a Process Capability Analysis for key characteristics, production processes, and control methods to be used during the performance of this contract. A key process shall be defined as a process that produces or effects one or more product characteristics that compose the products fit, function; or a process that is susceptible to variability such that the process inputs must be frequently adjusted to maintain a capability of 1.33 or higher. The Capability Analysis shall be made available for Government review. The Government and Contactor shall jointly determine the part numbers and characteristics that shall be analyzed. The analysis shall demonstrate that the product is compatible with current manufacturing processes, and that all new or revised processes can produce parts within tolerance with a Cpk of 1.33 or greater. The analysis shall also include quantitative metrics-based producibility analyses directed at minimizing procurement unit cost, reducing long lead time items, and mitigating manufacturing process risk, to ensure that design characteristics are compatible with economic production methods.

2.10.16 Variability Reduction

The contractor shall establish and maintain a variability reduction program with the objective of continuous product improvement and variability reduction for selected key characteristics and operations to be performed under this contract at the prime and subcontractor/supplier facilities. The Contractor and subcontractors/suppliers shall use variability reduction methods for improving process capability on any process that demonstrates a process capability less than 1.33. The contractor shall identify each key product/process characteristic along with measurable metrics. The contractor shall define methodologies for improvement of each characteristic and insure that preventive and corrective action is an integral part of product and process optimization. Product and process characteristics shall be continuously monitored and evaluated by the contractor for improvements as they mature.

2.10.17 Statistical Process Control (SPC)

The contractor shall manage and improve process performance through the evaluation of product quality at the contractor and subcontractor/supplier facilities, using SPC techniques. The contractor shall write a plan implementing SPC techniques using Guidelines for Implementation of Statistical Process Control ISO/DIS 11462-1 as a guide and make it available for government review prior to initiation of normal production. This plan is subject to disapproval by the Government following a determination that it lacks the capability to provide sufficient control of key product characteristics. The contractor agrees to maintain current, and make available, all documents/records required by the SPC plan for Government review at any time throughout the life of the contract and for five years after final delivery on the contract.

3. Suggested Section L and M inputs

3.1. Instructions to Offerors Guidance (Section L):

1. Manufacturing Readiness Level Demonstration. The offeror's proposal shall identify those elements (systems, subsystems, suppliers, and/or processes) being assessed for manufacturing risk and their current Manufacturing Readiness Levels using the criteria and process identified in the Manufacturing Readiness Level Deskbook. The contractor shall describe the approach used to assess the MRLs. For any element that is assessed to be below the target MRL of 'X', the offeror shall identify the current MRL and the plan to achieve the target MRL.

(Note: DFARS Subpart 215.304 requires that the manufacturing readiness of offerors be considered during source selection for ACAT I programs.)

2. Manufacturing Plan. The offeror shall describe:

a. How their manufacturing management system meets the requirements of AS6500A.
b. The major assembly sequence chart and anticipated manufacturing process flow.
c. The manufacturing build schedule, including drawing release; tooling design, build, and proofing; key supplier deliveries; and fabrication, assembly, and delivery schedules.
d. Facility requirements and layouts.
e. The offeror's plans to provide the needed manpower, facilities, and equipment for expected delivery rates.

3. Quality Systems. The offeror shall describe how their quality system assures product quality; achieves stable, capable processes; prevents defects; and employs effective methods for conducting root cause analyses and implementation of corrective actions.

4. Supplier Management. The offeror shall describe their:

a. Approach to selecting and managing key suppliers.
b. Processes for integration of key supplier activities into the overall program plan to assure that supplier activities support the overall program performance.
c. Specific supplier risks to the program and plans for mitigating those risks.
d. Plan for preventing the intrusion of counterfeit parts in factory equipment and delivered products.

3.2. Evaluation Criteria Guidance (Section M):

1. Manufacturing Readiness Level Demonstration. The offeror's proposal will be evaluated on the maturity of their proposed manufacturing capability, the adequacy of their supporting documentation to justify this capability, and the adequacy of the offeror's process and plans to achieve the target MRL as described in the Manufacturing Readiness Level Deskbook.

This sub-factor is met when the offeror's proposal identifies the elements being assessed for manufacturing readiness and their current MRLs. As described in the proposal, the offeror's

MRL assessment process is consistent with the MRL Deskbook. For elements that are below the target MRL, the proposal describes an achievable plan to meet the target MRL.

2. Manufacturing Plan. This sub-factor evaluates the proposed methods, schedules, and resources for producing the required products. This sub-factor is met when the offeror's proposal:

a. Describes how their manufacturing management system meets the requirements of AS6500A.
b. Describes the major assembly sequence and manufacturing process flows.
c. Includes an integrated, achievable schedule incorporating design, tooling, supplier, fabrication, assembly, and delivery milestones.
d. Describes facility requirements and layouts.
e. Describes achievable plans to provide the needed manpower, facilities, and equipment for expected delivery rates.

3. Quality Systems. This sub-factor evaluates the offeror's planned quality assurance system. This sub-factor is met when the offeror's proposal describes policies and practices that will:

a. Assure product quality.
b. Achieve stable, capable processes.
c. Prevent defects.
d. Result in effective root cause analyses and corrective actions.

4. Supplier Management. This sub-factor evaluates the offeror's proposed supplier management program. This sub-factor is met when the offeror's proposal:

a. Describes how key suppliers are selected and managed.
b. Describes how supplier activities will be integrated into the overall program plan.
c. Lists specific supplier risks and achievable plans for mitigating those risks.
d. Describes effective plans for preventing the intrusion of counterfeit parts in factory equipment and delivered products.

4. FAR/DFARS Clauses

Although the Contracting Officer is ultimately responsible for applying the appropriate FAR and DFARS clauses to the contract, the following sections address topics relevant to the Manufacturing and Quality function. Manufacturing and Quality Subject Matter Experts should be familiar with the requirements of these sections and offer their support and recommendations to the Contracting Officer.

4.1. Higher Level Quality Requirements

FAR Part 46, "Quality Assurance," prescribes the use of various FAR clauses that address quality and inspection requirements, depending upon the nature of the contract. For critical or complex items, clause 52.246-11 must be included in the contract. This clause requires the identification of a specific higher-level contract quality standard. Section 46.202-4 lists examples, such as ISO 9001 and AS9100. The Manufacturing/Quality Subject Matter Expert should work with the Contracting Officer to ensure the appropriate clause is included in the contract and the appropriate higher-level quality requirement is included in 52.246-11.

4.2. Counterfeit Parts Prevention

DFARS 246.870-3 prescribes the use of clauses 252.246-7007, "Contractor Counterfeit Electronic Part Detection and Avoidance System," and 252.246-7008, "Sources of Electronic Parts" when procuring electronic parts or end items that contain electronic parts.

4.3. First Article Approvals

FAR Subpart 9.3 governs First Article Testing and Approval and describes when this testing is required. When it is required, Subpart 9.3 requires either FAR clause 52.209-3 for contractor testing or 52.209-4 for government testing.

4.4. Contract Administration Functions

FAR Subpart 42.302, "Contract Administration functions," lists the activities performed by the Contract Administration Office (typically DCMA.) Manufacturing & Quality-related functions include activities such as performing production surveillance and status reporting, conducting pre-award surveys, monitoring industrial labor relations, ensuring contractor compliance with contractual quality assurance requirements, and reviewing waivers and deviations.

4.5. Labor Relationships

FAR Part 22 describes the government's policies and practices regarding labor relations at contractor facilities. Subpart 22.103-5 prescribes the use of Clause 52.222-1 to require the contractor to notify the government of labor disputes.

4.6. Government Property

FAR Part 45 governs the use of government property. Subpart 45.107 prescribes the use of Clause 52.245-1 when government property is being used.

4.7. Records Retention

FAR Subpart 4.7 governs records retention. Many Manufacturing and Quality-related items, such as receiving and inspection reports, purchase orders, and quality control and inspection records must be retained for four years.

4.8. Contractor Debarment, Suspension, and Ineligibility

FAR Subpart 9.4 discusses reasons that contractors may not be allowed to obtain government contracts. This includes limitations on subcontracting (Subpart 9.405-2). Most contracts must include Clause 52.209-6 that protects the government's interests when subcontracting with debarred (or soon to be debarred) or suspended suppliers.

APPENDIX E: EXAMPLE PRODUCIBILITY PROGRAM PLAN TOPICS

The contractor should discuss their approach and status for the following topics as appropriate for each program-unique requirement:

Overview of Organizational Approach to Producibility

- Corporate policies and command media.
- Applicable industry standards for producibility and manufacturability.
- Cross-functional organizations that participate in the producibility program.
- Producibility role(s) and relationship(s) of geographically separated manufacturing locations.
- Process to approve design and engineering change proposals.

Producibility Organization

- IPT structure with specific organization and names.
- Identification of manufacturing and quality–related IPT members and roles.
- IPT products and timing.
- Producibility approach and flow down of requirements to subcontractors.
- Involvement and integration of major and critical suppliers in producibility.

Producibility Goals and Milestones

- Identify design trade studies that will include manufacturing.
- Determine the manufacturing role in engineering technical reviews and audits.

Design Considerations

- Design for Manufacture and Assembly (DFMA).
- Materials selection.
- Design to Cost goals.
- Design Standards.
- Key Characteristics.
- Critical Characteristics.
- Critical manufacturing processes.
- Digital engineering and CAD/CAM formats.
- Technical Data Package data format and translation standards.

- Use of Additive Manufacturing for rapid prototyping.
- Identification of complex or difficult manufacturing processes.
- Identification of foreign or single source materials and components.
- Standardization of design, materials, and components.
- Risks, issues, and mitigation plans.

Manufacturing Processes

- Lean/Six Sigma.
- Process Capability.
- Statistical Process Control.
- Measurement System Analysis.
- Calibration.
- Variability Reduction.
- PFMEA and FMEA.
- Factory Floor Modeling and Simulation.
- Use of automation, robotics, etc.
- Additive Manufacturing for production.
- Additive Manufacturing parts approval, qualification, certification, verification, and validation.
- Manufacturing Work Instructions.
- Production Part Approval Process.
- Identification of new or unproven materials or manufacturing processes.
- Hazardous materials.
- Safety and risk mitigation plans.
- Manufacturing technology and manufacturing maturation requirements.
- Risks, issues, and mitigation plans.

Transition to Production

- Manufacturing Readiness Assessments (or MRL assessments).
- Production Readiness Reviews.
- Supplier PRR approach.
- Tooling, equipment, facilities, etc.

- Workforce planning, skills, and availability.
- Critical manufacturing skills.
- Risk mitigation for Diminishing Manufacturing Sources and Materials Sources.
- Supply chain quality management.
- Risks, issues, and mitigation plans.

Opportunities for Enhancements

- Producibility processes and plan.
- Material changes.
- Resource planning.
- Facility improvements.
- Development of manufacturing technology.
- Redesign of special purpose tooling and equipment.
- Changes to improve procedures.
- Redesign for manufacturing.
- Safety and ergonomics for effective design and operation.
- DMSMS risk mitigation.
- Value Engineering.

GLOSSARY

Accessibility: A measure of the relative ease of admission to the various areas of an item for operation or maintenance. (DAU)

Analysis of variance (ANOVA): A basic statistical technique for determining the proportion of influence a factor or set of factors has on total variation. It subdivides the total variation of a data set into meaningful component parts associated with specific sources of variation to test a hypothesis on the parameters of the model or to estimate variance components. There are three models: fixed, random, and mixed. (ASQ)

Additive manufacturing: A process of joining materials to make parts from three-dimensional model data, usually layer by layer, also known as three-dimensional printing. (DAU)

Balancing the line: The process of evenly distributing the quantity and variety of work across available work time, avoiding overburden and underuse of resources. This eliminates bottlenecks and downtime, which translates into shorter flow time. (ASQ)

Calibration: Comparison of an item against a known standard. (DAU)

Cloud computing: A model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and read with minimal management effort or service provider interaction. (NIST SP 800-145)

Computer-aided design (CAD): A type of software used by architects, engineers, drafters, and artists to create precision drawings or technical illustrations. CAD software can be used to create 2-D drawings or 3-D models. (ASQ)

Computer-aided engineering (CAE): A broad term used by the electronic design automation industry for the use of computers to design, analyze, and manufacture products and processes. CAE includes computer-aided design (CAD) and computer-aided manufacturing (CAM), which is the use of computers for managing manufacturing processes. (ASQ)

Computer-aided manufacturing (CAM): Use of software to control machine tools in the manufacturing of products. (U.S. Office of Technology Assessment)

Concurrent engineering (CE): A way to reduce cost, improve quality, and shrink cycle time by simplifying a product's system of life cycle tasks during the early concept stages. (ASQ)

Control chart: A time-sequenced chart with upper and lower control limits on which values of some statistical measure for a series of samples or subgroups are plotted. The chart frequently shows a central line to help detect a trend of plotted values toward control limit. (ASQ)

Control limits: The natural boundaries of a process within specified confidence levels, expressed as the upper control limit (UCL) and the lower control limit (LCL). (ASQ)

Concurrent engineering: A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. Intended to cause developers, from the beginning, to consider all elements of the system life cycle from requirements development through disposal, including cost, schedule, and performance. (DAU)

Commercial off-the-shelf (COTS): A software and/or hardware product that is commercially ready-made and available for sale, lease, or license to the general public. (CNSSI 4009)

Cost of quality (CoQ): (Another term for cost of poor quality (COPQ)). The cost of providing poor quality products or services. There are four categories: internal failure costs (costs associated with defects found before the customer receives the product or service), external failure costs (cost associated with defects found after the customer receives the product or service), appraisal cost (costs incurred to determine the degree of conformance to quality requirements), and prevention costs (costs incurred to keep failure and appraisal cost to a minimum). (ASQ)

Cp (process capability): The ratio of tolerance to 6 sigma, or the upper specification limit (USL) minus the lower specification limit (LSL) divided by 6 sigma. It is sometimes referred to as the engineering tolerance divided by the natural tolerance and is only a measure of dispersion. (ASQ)

Cpk (process capability index): Equals the lesser of the USL minus the mean divided by 3 sigma (or the mean) minus the LSL divided by 3 sigma. The greater the Cpk value, the better. (ASQ)

Critical Design Review (CDR): A review conducted to determine that the detailed design satisfies the performance and engineering requirements of the development specification; to establish the detailed design compatibility among the item and other items such as equipment, facilities, computer programs, and personnel; to assess producibility and risk areas; and to review the preliminary product specifications.

Critical incident technique: An advanced tool for root cause analysis that can aid in the search for causes through interviews of various people involved in the process in which a critical event occurred.

Critical processes: Processes that present serious potential dangers to human life, health, and the environment, or that risk the loss of significant sums of money or customers. (ASQ)

Critical characteristic (CC): 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. (SAE)

Critical characteristic (alternate): A characteristic that analysis indicates is likely, if defective, to create or increase a hazard to human safety, or to result in failure of a system to perform a required function. (DAU)

Critical safety item: A part, assembly, installation, or production system with one or more critical safety characteristics that, if missing or not conforming to the design data, quality

requirements, or overhaul and maintenance documentation, would result in an unsafe condition. (DAU)

Critical technology: Those technologies that may pose major technological risk during development, particularly during the Engineering and Manufacturing Development (EMD) phase of acquisition. (DAU)

Critical technology element: A new or novel technology that a platform or system depends on to achieve successful development or production or to successfully meet a system operational threshold requirement. (DAU)

Critical technical parameter: A measurable critical system characteristic that, when achieved, allows the attainment of a desired operational performance capability. (DAU)

Defect: Any variation in a required characteristic of a product or its parts that is far enough removed from its target value to prevent the product from fulfilling the physical and/or functional requirements of the customer or specification. (NAVSO P-3687)

Derating: Using an item so that applied stresses are below the item's rated values, i.e., stress values that the item would normally be expected to withstand. (DAU)

Design Failure Modes and Effects Analysis (DFMEA): A technique used to analyze, prior to entering the manufacturing phase of development, a part's design to identify potential failures, errors, and defects and their effect on cost and risk. (NAVSO P-3687)

Design for manufacturing (DFM): The engineering practice of designing products so they are easy to manufacture. (Wikipedia.org)

Design for manufacturing and assembly (DFMA): A technique used to achieve the optimum balance between design objectives, manufacturing and assembly requirements, and process capabilities. (NAVSO P-3687)

Design guidelines: A compilation of knowledge expressed either in hard copy or electronic media that maybe used by the design engineer or the Integrated Product Team to design the product to optimize its producibility. (NAVSO P-3687)

Design of experiments (DOE): A branch of applied statistics dealing with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. (ASQ)

Design parameter: Qualitative and quantitative aspects of physical and functional characteristics of a component, device, product, or system that are input to its design process. Design parameters determine cost, design, and risk trade-offs in the item's development. (DAU)

Digital engineering: An integrated, computation-based approach that uses authoritative sources of system data and models as a continuum across disciplines to support life cycle activities. (MIL-HDBK-539)

Digital engineering (alternate): An integrated digital approach using authoritative sources of system data and models as a continuum throughout the development and life of a system. Digital engineering updates traditional systems engineering practices to take advantage of computational technology, modeling, analytics, and data sciences. Across the Services and industry, digital engineering is a necessary practice to support acquisition in an environment of increasing global challenges and dynamic threat environments. (DoD DE Strategy)

Digital thread: A communication framework that connects a system's data across functional perspectives. (MIL-HDBK-539)

Digital twin: The electronic representation—the digital representation—of a real-world entity, concept, or notion, either physical or perceived. (NISTR 8356)

Efficient: Achieving maximum productivity with the optimal resources. (ASQ)

Engineering change proposal (ECP): The documentation by which a proposed engineering change is submitted to the responsible authority, recommending that a change to an original item of equipment be considered and the design or engineering change be incorporated into the article to modify, add to, delete, or supersede original parts. (DAU)

Environmental stress screening: A series of test conducted under environmental stress to expose weak parts and defects in workmanship so they may be corrected. (DAU)

Error proofing: Improving designs to prevent mistakes from being made. Contrasted with mistake proofing, which is improving processes to prevent mistakes from being made or passed downstream. Some consider the terms to be synonymous and applicable to both products and processes. (ASQ)

Failure Mode[s] and Effects Analysis (FMEA): A systematized group of activities to recognize and evaluate the potential failure of a product or process and its effects, identify actions that could eliminate or reduce the occurrence of the potential failure and document the process. (ASQ)

Failure Modes, Effects, and Criticality Analysis (FMECA): Procedure by which each potential failure mode is analyzed to determine its effects on the system and then classified according to its severity. It further attempts to identify all single points of failure, that is, those points where failure of the component can cause failure of the entire system. (DAU)

Fatigue allowance: Time included in the production standard to allow for decreases or losses in production that might be attributed to worker fatigue. (Usually applied as a percentage of the leveled, normal, or adjusted time.) (DAU)

First article testing (FAT): Production testing that is planned, conducted, and monitored by the materiel developer. FAT includes preproduction and initial production testing conducted to ensure that the contractor can furnish a product that meets the established technical criteria. (DAU)

Functional layout: The practice of grouping machines (such as grinding machines) or activities (such as order entry) by type of operation performed. (ASQ)

Gage repeatability and reproducibility (GR&R): The evaluation of a gauging instrument's accuracy by determining whether its measurements are repeatable (there is close agreement among several consecutive measurements of the output for the same value of the input under the same operating conditions) and reproducible (there is close agreement among repeated measurements of the output for the same value of input made under the same operating conditions over a period of time). (ASQ)

Geometric dimensioning and tolerancing (GD&T): A set of rules and standard symbols to define part features and relationships on an engineering drawing depicting the geometric relationship of part features and allowing the maximum tolerance that permits full function of the product. (ASQ)

In-control process: A process in which the statistical measure being evaluated is in a state of statistical control; in other words, the variations among the observed sampling results can be attributed to a constant system of chance causes. See also "out-of-control process." (ASQ)

Industrial base: That part of the total private- and government-owned industrial production and depot-level equipment and maintenance capacity in the United States and its territories and possessions and Canada. It is or will be made available in an emergency for the manufacture of items required by the U.S. Military Services and selected allies. (DAU)

Industrial engineering: The art and science of coordinating personnel, equipment, and materials to attain a desired quantity of output at a specified time and at an optimum cost. This may include gathering, analyzing, and acting upon facts pertaining to building and facilities, layouts, personnel organization, operating procedures, methods, processes, schedules, time standards, wage rates, wage payment plans, costs, and systems for controlling the quality and quantity of goods and services. (DAU)

Interface: The functional and physical characteristics required to exist at a common boundary or connection between persons, between systems, or between persons and systems. A system external to the system being analyzed that provides a common boundary or service that is necessary for the other system to perform its mission in an under-graded mode, e.g., a system that supplies power, cooling, heating, air services, or input signals. (DAU)

Job instruction (work instruction): Quality system documentation that describes work conducted in one function in an organization, such as setup, inspection, rework, or operator. (ASQ)

Key characteristic: 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. (SAE)

Key process: A major system-level process that supports the mission and satisfies major consumer requirements. (ASQ)

Key process characteristic: A process parameter that can affect safety or compliance with regulations, fit, function, performance, or subsequent processing of product. (ASQ)

Key product characteristic: A product characteristic that can affect safety or compliance with regulations, fit, function, performance, or subsequent processing of product. (ASQ)

Kitting: A process in which assemblers are supplied with kits—a box of parts, fittings, and tools—for each task they perform. This eliminates time-consuming trips from one parts bin, tool crib or supply center to another to get necessary materials. (ASQ)

Manufacturability: The ease of manufacturing and production (producibility also encompasses other dimensions of the production task). (SE BoK)

Manufacturing feasibility estimate/assessment: An assessment conducted to identify potential manufacturing constraints and risks and the capability of the contractor to execute the manufacturing efforts. (MIL-STD-1528A)

Modeling and Simulation: The use of models and simulations, either statically or over time, to develop data as a basis for making managerial or technical decisions. This includes but is not limited to emulators, prototypes, simulators, and stimulators. (MIL-STD-3022, Change 1)

Monte Carlo Simulation: A simulation in which random statistical sampling techniques are employed to determine estimates for unknown values, i.e., making a random draw. (SISO-FEF-020-2007)

Out-of-control process: A process in which the statistical measure being evaluated is not in a state of statistical control. In other words, the variations among the observed sampling results cannot be attributed to a constant system of chance causes. (ASQ)

Pareto Analysis: A method, using vertical bar graphs, to display occurrences in a prioritized order. Occurrences are taken for a specific timeframe of the event measured. (NAVSO P-3687)

Poka-yoke: A Japanese term for a manufacturing technique for preventing mistakes by designing the manufacturing process, equipment, and tools so an operation literally cannot be performed incorrectly. In addition to preventing incorrect operation, the technique usually provides a warning signal of some sort for incorrect performance. (ASQ)

Process capability: A statistical measure of the inherent process variability of a given characteristic. (ASQ)

Process capability: A comparison of the output of an *in-control* process to the specification limits by using *capability indices.* The comparison is made by forming the ratio of the spread between the process specifications (the specification “width”) to the spread of the process values, as measured by 6 process standard deviation units (the process “width”). (NIST)

Process capability index: The value of the tolerance specified for the characteristic divided by the process capability. The several types of process capability indexes include the widely used Cpk and Cp. (ASQ)

Process control: The method for ensuring that a process meets specified requirements. (ASQ)

Process Failure Modes and Effects Analysis (PFMEA): A means for analyzing manufacturing processes to identify potential problems that may induce part defects. (NAVSO P-3687)

Process flow diagram: A visual depiction, generally using symbols, of the flow of materials or information through a process. Also called a process flowchart. (ASQ)

Producibility: The combined effect of those elements or characteristics of a design and the production planning for it that enables the item, described by the design, to be produced and inspected in the quantity required and that permits a series of trade-offs to achieve the optimum of the least possible cost and the minimum time, while still meeting the necessary quality and performance requirements. (DAU)

Producibility (alternate): The relative ease by which a product can be manufactured as measured in yield, cycle times, and the associated costs of options in product designs, manufacturing processes, production and support systems, and tooling. (NAVSO P-3687)

Producibility analysis: The comparison of alternative design materials, processes, and manufacturing techniques to determine the most economical manufacturing processes and materials to "produce a product while meeting performance specifications and required production rates". (MIL -STD1528A)

Producibility assessment worksheet (PAW): Documented expert opinion that is used as a means of identifying potential problem areas related to the producibility of a product. (NAVSO P-3687)

Production engineering: The application of design and analysis techniques to produce a specified product. Included are the functions of planning, specifying, and coordinating the application of required resources; performing analyses of producibility and production operations, processes, and systems; applying new manufacturing methods, tooling, and equipment; controlling the introduction of engineering changes; and employing cost control techniques. (DAU)

Producibility engineering planning (PEP): Designing producibility into a system so that production is feasible and optimizing production so the system can be produced at least cost. (LMI)

Product Life-cycle Management (PLM): The process or system used for managing product-related design, production and maintenance information. PLM systems are typically software applications designed for the purpose of life cycle management of a product. (MIL-STD-31000B)

Producibility program plan: A program plan under which the producibility analysis will be conducted; not to be confused with the actual producibility analysis. The program plan details the organizational structure, authority, and responsibilities of the personnel that will be used to monitor producibility and perform the required analyses. (MIL-HDBK-727)

Producibility system: The integrated process and resources needed to successfully achieve producibility. (NAVSO P-3687)

Product and manufacturing information (PMI): Data pertinent to manufacturing a product including information such as tolerances, reference dimensions, data points for quality processes, surface finish, material specifications, etc. This data has historically been included in drawings to be used in manufacturing operations. MCAD solutions may also store the PMI in the 3D CAD model, from where it can be added automatically to drawings or accessed by viewing the 3D CAD model. (CIMdata Glossary)

Production part approval process (PPAP): A customer part qualification process for purchased parts or materials that are to be used in the customer's final product. Customer PPAP approval, or a deviation, is required before shipping the purchased parts or materials to the customer for use in their production process. Its purpose is to determine whether all customer engineering design record requirements are properly understood by the supplier and that the process has the potential to produce product consistently meeting these requirements. (ASQ)

Production plan/manufacturing plan: The document that describes the employment of the manufacturing resources to produce the required products or systems on time and within cost constraints. Synonymous with Manufacturing Plan. (DAU)

Production Readiness Review (PRR): A formal review of a program to determine if the design is ready for production, if production engineering problems have been resolved, and if the producer has accomplished adequate planning for the production phase. (NAVSO P-3687)

Quality: A subjective term for which each person or sector has its own definition. In technical usage, quality can have two meanings: (1) the characteristics of a product or service that bear on its ability to satisfy stated or implied needs; (2) a product or service free of deficiencies. According to Joseph Juran, quality means "fitness for use"; according to Philip Crosby, it means "conformance to requirements. (ASQ)

Quality assurance (QA): A planned and systematic pattern of all actions necessary to provide confidence that adequate technical requirements are established, that products and services conform to established technical requirements, and that satisfactory performance is achieved. (DAU)

Quality control (QC): The system or procedure used to check product quality throughout the acquisition process. (DAU)

Quality function deployment (QFD): A structured method in which customer needs or expectations are translated into appropriate technical requirements for each stage of product development and production. The QFD process is often referred to as listening to the voice of the customer (VOC). (ASQ)

Quality loss function: A parabolic approximation of the quality loss that occurs when a quality characteristic deviates from its target value. The quality loss function is expressed in monetary units: the cost of deviating from the target increases quadratically the farther the quality

characteristic moves from the target. The formula used to compute the quality loss function depends on the type of quality characteristic being used. The quality loss function was first introduced in this form by Genichi Taguchi. (ASQ)

Quality management system (QMS): A formal system that documents the structure, processes, roles, responsibilities, and procedures required to achieve effective quality management.

Rapid prototyping: In the context of manufacturing and production (versus the Middle Tier of Acquisition Rapid Prototyping pathway), a process for quickly transforming a design into a three-dimensional, physical model. (NAVSO P-3687)

Realization factor: The ratio of actual performance time to a standard performance time, usually expressed as a decimal number. (DAU)

Repeatability: The variation in measurements obtained when one measurement device is used several times by the same person to measure the same characteristic on the same product. (ASQ)

Reproducibility: The variation in measurements made by different people using the same measuring device to measure the same characteristic on the same product. (ASQ)

Root cause: A factor that caused a nonconformance and should be addressed with corrective action. (ASQ)

Root cause analysis: The method of identifying the cause of a problem, solving it, and preventing it from occurring again. Uncovering the correct and accurate reason(s) why something is happening or has already occurred. (ASQ)

Statistical process control (SPC): The application of statistical techniques to control a process. (ASQ)

Statistical process control (alternate): The use of statistical techniques to control a process or production method. SPC tools and procedures can help you monitor process behavior, discover issues in internal systems, and find solutions for production issues. (ASQ)

Technical data package: The authoritative technical description of an item. This technical description supports the acquisition, production, inspection, engineering, and logistics support of the item. The description defines the required design configuration and/or performance requirements, and procedures required to ensure adequacy of item performance. It consists of applicable technical data such as models, engineering design data, associated lists, specifications, standards, performance requirements, quality assurance provisions, software documentation, and packaging details. (DAU and MIL-STD-31000B)

Theory of constraints (ToC): A factory scheduling and inventory control philosophy that aims to improve factory flow and reduce inventory levels by recognizing the probabilistic nature of interdependent workstations. (DAU)

Tolerance analysis: A study of the deviation from nominal specifications that a component may have and still satisfy quality requirements. (NAVSO P-3687)

Trade study or trade-off analysis: A formal decision-making method that can be used to solve many complex problems. Used in producibility to rank potential design solutions against the product goals to highlight the manufacturing advantages and disadvantages of each design concept. (NAVSO P-3687)

Six Sigma: A quality approach used to obtain zero defects in production. (NAVSO P-3687)

Statistical process control (SPC): The application of statistical techniques to control a process; often used interchangeably with the term “statistical quality control.” (ASQ)

Value Engineering (VE): An organized/systematic approach that analyzes the functions of systems, equipment, facilities, services, and supplies to ensure they achieve their essential functions at the lowest life-cycle cost consistent with required performance, reliability, quality, and safety. (IDA, SD-24)

Value stream mapping: A pencil-and-paper tool used in two stages: (1) Follow a product’s production path from beginning to end and draw a visual representation of every process in the material and information flows. (2) Draw a future state map of how value should flow. The most important map is the future state map. (ASQ)

Voice of the customer (VOC): The expressed requirements and expectations of customers relative to products and services, as documented and disseminated to the providing organization’s members. (ASQ)

ACRONYMS

2D/3D	Two-Dimensional/Three-Dimensional
ACAT II/III	Acquisition Category II or III
AIAG	Automotive Industry Action Group
AM	Additive Manufacturing
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
AoA	Analysis of Alternatives
APQP	Advanced Product Quality Planning
AS	Acquisition Strategy
ASME	American Society of Mechanical Engineers
ASQ	American Society for Quality
ASR	Alternative Systems Review
BoK	Body of Knowledge
BOM	Bill of Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CC	Critical Characteristic
CDD	Capability Development Document
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CI	Critical Item
CM	Configuration Management
CMP	Critical Manufacturing Process
CPI	Continuous Process Improvement
CoQ	Cost of Quality
Cp/Cpk	Process Capability/ Process Capability Index
CSI	Critical Safety Item
CTE	Critical Technology Element
DARPA	Defense Advanced Research Projects Agency
DAU	Defense Acquisition University
DCMA	Defense Contract Management Agency

DE	Digital Engineering
DFARS	Defense Federal Acquisition Regulation Supplement
DFE	Design for Ergonomics
DFM	Design for Manufacturability
DFMA	Design for Manufacture and Assembly
DFMEA	Design Failure Modes and Effects Analysis
DFSS	Design for Six Sigma
DFT	Design for Test
DIB	Defense Industrial Base
DID	Data Item Description
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DoD	Department of Defense
DoDD	DoD Directive
DoDI	DoD Instruction
DoDM	DoD Manual
DOE	Design of Experiments
DSS	Design for Six Sigma
ECP	Engineering Change Proposal
DTRAM	Defense Technical Risk Assessment Methodology
EMD	Engineering and Manufacturing Development
ERP	Enterprise Resource Planning
ESS	Environmental Stress Screening
ETM	Engineering and Technical Management
EVM	Earned Value Management
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FA	First Article
FAI	First Article Inspection
FAT	First Article Test
FCA	Functional Configuration Audit
FDD	Full Deployment Decision
FFRDC	Federally Funded Research and Development Center
FMEA	Failure Modes and Effects Analysis

FMECA	Failure Modes, Effects, and Criticality Analysis
FRACAS	Failure Reporting, Analysis, and Corrective Action System
FRP	Full-Rate Production
FRPDR	Full-Rate Production Decision Review
Gage R&R	Gage Repeatability and Reproducibility
GD&T	Geometric Dimensioning and Tolerancing
GFE	Government-Furnished Equipment
GFM	Government-Furnished Material
GFP	Government-Furnished Property
GIDEP	Government and Industry Data Exchange Program
GOTS	Government Off-the-Shelf
HAZMAT	Hazardous Material
HVAC	Heating, Ventilation, and Air Conditioning
IB	Industrial Base
IBA	Industrial Base Assessment
IBAS	Industrial Base Analysis and Sustainment
ICA	Industrial Capabilities Assessments
ICD	Initial Capabilities Document
ICS	Industrial Control System
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industrial Internet of Things
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
INCOSE	International Council on Systems Engineering
IOC	Initial Operational Capability
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
IRAD	Independent Research and Development
ISO	International Organization for Standardization
ITRA	Independent Technical Risk Assessment
KC	Key Characteristics
KLP	Key Leadership Position

LSL	Lower Specification Limit
LRIP	Low-Rate Initial Production
M&S	Modeling and Simulation
ManTech	Manufacturing Technology
MBE	Model-Based Engineering
MBSE	Model-Based Systems Engineering
MCA	Major Capability Acquisition
MDA	Milestone Decision Authority
MDAP	Major Defense Acquisition Program
MDD	Materiel Development Decision
MEP	Manufacturing Extension Partnership
MES	Manufacturing Execution System
MII	Manufacturing Innovation Institute
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
M&Q	Manufacturing and Quality
MRA	Manufacturing Readiness Assessment
MRB	Material Review Board
MRL	Manufacturing Readiness Level
MRP/MRP II	Material Resource Planning
MS A	Milestone A
MS B	Milestone B
MS C	Milestone C
MSA	Materiel Solution Analysis
MSA	Measurement Systems Analysis
NAVSO-P	Navy Standard Operating Procedure
NDAA	National Defense Authorization Act
NIST	National Institute of Standards and Technology
O&S	Operations and Support
OSD	Office of the Secretary of Defense
OUSD(A&S)	Office of Under Secretary of Defense for Acquisition and Sustainment
OUSD(R&E)	Office of the Under Secretary of Defense for Research and Engineering
OT	Operational Technology

PAW	Producibility Assessment Worksheet
PCA	Physical Configuration Audit
P&D	Production and Deployment
PDF	Portable Document Format
PDR	Preliminary Design Review
PEP	Producibility Engineering and Planning
PFMEA	Process Failure Modes and Effects Analysis
PHL	Preliminary Hazard List
PHST	Packing, Handling, Storage, and Transportation
PLM	Product Life-cycle Management
PM	Program Manager
PMI	Product and Manufacturing Information
PMP	Parts, Materials, and Processes
PMO	Program Management Office
Pp/Ppk	Process Performance/Process Performance Index
PPAP	Production Part Approval Process
PPC	Production Planning and Control
PQM	Production, Quality, and Manufacturing
Pre-MDD	Pre-Materiel Development Decision
PRR	Production Readiness Review
QA	Quality Assurance
QC	Quality Control
QFD	Quality Function Deployment
QMS	Quality Management System
RCO	Rapid Capabilities Office
RIO	Risk, Issue, and Opportunity
RFP	Request for Proposal
RFP DP	Request for Proposal Release Decision Point
R&D	Research and Development
R&M	Reliability and Maintainability
RMBoK	Reliability and Maintainability Body of Knowledge
SAE	Society of Automotive Engineers
SE	Systems Engineering

SEMP	Systems Engineering Management Plan
SEP	Systems Engineering Plan
SFR	System Functional Review
SETR	Systems Engineering Technical Review
SIE	Special Inspection Equipment
SME	Society of Manufacturing Engineers
SOO	Statement of Objectives
SOW	Statement of Work
SPC	Statistical Process Control
SPI	Special Packaging Instructions
SRR	System Requirements Review
SSP	Source Selection Plan
ST	Special Tooling
S&T	Science and Technology
STE	Special Test Equipment
STEP	Standard for the Exchange of Product Model Data (ISO 10303)
SVR	System Verification Review
TDP	Technical Data Package
TMRR	Technology Maturation and Risk Reduction
TOC	Theory of Constraints
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
USL	Upper Specification Limit
USD(R&E)	Under Secretary of Defense for Research and Engineering
USC	United States Code
VE	Value Engineering
VECP	Value Engineering Change Proposal
VSM	Value Stream Mapping
WBS	Work Breakdown Structure

REFERENCES

Resources related to the guide are listed below and may contain links to the referenced document. As many of these resources are revised frequently, readers are advised the documents may change or may be updated, replaced, or cancelled. Readers may need to conduct an internet search to find the most recent version.

Federal Laws and Regulations

Defense Federal Acquisition Regulation Supplement (DFARS) 246.870-3, "Contractors Counterfeit Electronic Part Detection and Avoidance."

Defense Federal Acquisition Regulation Supplement (DFARS) 252.246-7007, "Contractor Counterfeit Electronic Part Detection and Avoidance System."

Defense Federal Acquisition Regulation Supplement (DFARS) 252.246-7008, "Sources of Electronic Parts."

Federal Acquisition Regulation (FAR) Part 48, "Value Engineering," 2023. https://www.acquisition.gov/far/part-48

Federal Acquisition Regulation (FAR) Part 52.248-1, "Value Engineering," 2023. https://www.acquisition.gov/far/52.248-1

OMB A-131. "Value Engineering." Circular No. A-131. Office of Management and Budget (OMB), May 2013.

10 USC 1706. "Government Performance of Certain Acquisition Functions."

10 USC 4820 (formerly 2440). "National Technology and Industrial Base Plans, Policy, and Guidance."

10 USC 4272 (formerly 2448b). "Independent Technical Risk Assessments."

10 USC 4817 (formerly 2508). "Industrial Base Fund."

50 USC 55. Defense Production Act, Chapter 55, "Defense Production," 1950.

DoD Issuances

https://www.esd.whs.mil/Directives/issuances/dodd/

DoD Directive 4200.15, "Manufacturing Technology (ManTech) Program," October 2018.

DoD Handbook 5000.60H, "Assessing Defense Industrial Capabilities," April 1996.

DoD Instruction 4245.14, "DoD Value Engineering Program," October 2012.

DoD Instruction 4245.15, “Diminishing Manufacturing Sources and Material Shortages Management,” November 2020.

DoD Instruction 5000.85, “Major Capability Acquisition,” August 2020.

DoD Instruction 5000.84, “Analysis of Alternatives”

DoD Instruction 5000.88, “Engineering of Defense Systems,” November 2020.

DoD Instruction 5000.93, “Use of Additive Manufacturing in the DoD,” July 2021.

DoD Instruction 5000.94, “Use of Robotic Systems for Manufacturing and Sustainment in the DoD,” March 2022.

DoD Instruction 5000.97, “Digital Engineering,” December 2023.

DoD Manual 4120 Defense Standardization Program (DSP) Procedures.

DoD Manual 4242.15, “Management of Diminishing Sources and Material Shortages,” October 2022.DoD Instruction 5000.60, “Defense Industrial Capabilities Assessments,” July 2014.

DoD Manual 4245.7-M “Transition from Development to Production,” September 1985. https://apps.dtic.mil/dtic/tr/fulltext/u2/a303209.pdf

Guidance

Air Force Instruction (AFI) 63-145, Manufacturing and Quality Management, December 2020. https://static.e-publishing.af.mil/production/1/saf_aq/publication/afi63-145/afi63-145.pdf

Best Practices for Using Systems Engineering Standards (ISO/IEC/IEEE 15288, IEEE 15288.1, and IEEE 15288.2) on Contracts for Department of Defense Acquisition Programs, DoD, April 2017.

DCMA-INST-3401, Defense Industrial Base Mission Assistance. https://www.dcma.mil/Portals/31/Documents/Policy/DCMA-INST-3401.pdf

DCMA-INST 401, Industrial Analysis https://www.dcma.mil/Portals/31/Documents/Policy/DCMA-INST-401.pdf

DCMA Manual 3401-05, Defense Industrial Base Monitoring and Reporting, 2020.

Defense Technical Risk Assessment Methodology (DTRAM). Office of the Under Secretary of Defense for Research and Engineering. https://www.cto.mil/wp-content/uploads/2023/05/DTRAM-6-4-May2023.pdf

Design for Producibility (Air Force), Ballistic Missile Organization, 1990.

Department of the Navy. NAVSO P-3687, Producibility Systems Guidelines, December 1999. http://everyspec.com/USN/NAVY-General/NAVSO_P-3687_8510/

Department of the Navy. Best Practices for Transitioning from Development to Production. NAVSO P-6071, Washington, 1986.DoD Data Strategy, October 2020.

Digital Engineering Body of Knowledge (DEBoK), February 2022. https://www.dodtechipedia.mil/dodwiki/pages/viewpage.action?pageId=760447627

DoD Digital Engineering Strategy, Office of the Under Secretary of Defense for Research and Engineering, June 2018. https://www.cto.mil/sea/pg

DoD Manufacturing and Quality (M&Q) Body of Knowledge, January 2021 (or latest version). https://www.cto.mil/sea/mq

DoD Risk, Issue, and Opportunity (RIO) Management Guide for Defense Acquisition Programs, Office of the Deputy Assistant Secretary of Defense for Systems Engineering, January 2017. https://www.cto.mil/sea/pg

DoD Systems Engineering Plan (SEP) Outline, Version 4.1, Office of the Under Secretary of Defense for Research and Engineering, May 2023. https://www.cto.mil/sea/pg

Early Manufacturing and Quality (M&Q) Engineering Guide, Office of the Under Secretary of Defense for Research and Engineering, July 2021. https://www.cto.mil/sea/mq

Engineering of Defense Systems Guidebook, Office of the Under Secretary of Defense for Research and Engineering, February 2022. https://www.cto.mil/sea/pg

Guide for Integrating Systems Engineering into DoD Acquisition Contracts, Office of the Under Secretary of Defense for Research and Engineering (Forthcoming).

Manufacturing Readiness Level (MRL) Deskbook. MRL Working Group, 2022. https://www.dodmrl.org/

MIL-HDBK-61B, Configuration Management Guidebook, 2020.

MIL-HDBK-245D, DoD Handbook for Preparation of Statement of Work, 1996.

MIL-HDBK-338B, Electronic Reliability Design Guidebook, 1998.

MIL-HDBK-454B, General Guidelines for Electronic Equipment, Guideline 78: Producibility, 2007.

MIL-HDBK-470A, Designing and Developing Maintainable Products and Systems, Rev. A, Notice 2, 2012.

MIL-HDBK-536, DoD Digital Engineering and Modeling Practices Handbook, 2022.

MIL-HDBK-727, Design Guidance for Producibility, April 1984. http://everyspec.com/MIL-HDBK/MIL-HDBK-0700-0799/MIL_HDBK_727_1853/

MIL-HDBK-896A, Manufacturing Management Program Guide, 2016.

MIL-HDBK-2155, Failure Reporting, Analysis and Corrective Action Taken, Notice 2, 2019.

RIO. Risk, Issue, and Opportunity (RIO) Management Guide for Defense Acquisition Programs. Office of the Under Secretary of Defense for Research and Engineering, 2023.

SD-19, Parts Management Guide. Defense Standardization Program Office, December 2013. .

SD-22, Diminishing Manufacturing Sources and Material Shortages, A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program. Defense Standardization Program Office, May 2022.

SD-24, Value Engineering: A Guidebook of Best Practices and Tools, Office of Assistant Secretary of Defense, Systems Engineering, 2011.

SD-26, DMSMS and Parts Management Contracting Guide, Defense Standardization Program Office, June 2023.

Systems Engineering Guidebook. Office of the Under Secretary of Defense for Research and Engineering, February 2022. https://www.cto.mil/sea/pg

Technology Readiness Assessment (TRA) Guidebook. Office of the Under Secretary of Defense for Research and Engineering, 2023. https://www.cto.mil/sea/pg

Data Item Descriptions

DI-MGMT-80797A, Producibility Analysis Report.

DI-MGMT-81889B, Manufacturing Plan.

DI-SDMP-81476A, DoD Manufacturing Process Standards Documents.

DI-SESS-81012, Proposed Critical Manufacturing Processes.

DI-SESS-80639, Engineering Change Proposal.

DI-SESS-80640, Request for Variance.

DI-SESS-80858, Supplier's Configuration Management Plan.

DI-STDZ-81993, Parts, Materials, and Processes Management Plan.

DI-SESS-81253, Configuration Status Accounting (CSA) Information.

Standards

ASME B89.7.3.1-2019, Guidelines for Decision Rules: Considering Measurement Uncertainty Determining Conformance to Specifications.

ASME Y14.5-2018, Dimensioning and Tolerancing Standard.

ASME Y14.41-2019, Digital Product Data Definition Practices.

ASTM Standard E2782-2022, Standard Guide for Measurement Systems Analysis.

DOD-STD-2101, DoD Standard Practice: Classification of Characteristics, 1979.

IEEE 1149.1 (2013), Standard for Test Access Port and Boundary-Scan Architecture.

IEEE 1149.1, (JTAG) Testability Primer.

IEEE 15288.2, Standard for Technical Reviews and Audits on Defense Programs, 2015.

ISO 10303 (2000), Standard for the Exchange of Product Model Data.

ISO 1101:2004, Geometrical Product Specifications, Geometric Tolerancing.

ISO 10012:2003, Measurement Management Systems: Requirements for Measuring Processes and Measuring Equipment.

ISO/IEC 17025:2017, Testing and Calibration Laboratories.

ISO 9000:2015/9001:2015, Quality Management System.

ISO 9001:2015, Quality Management System Requirements.

MIL-A-70625A, Military Specification, Automated Acceptance Inspection Equipment Design, Testing and Approval, and Notice 2 (April 2000).

MIL-STD-1916, Department of Defense Test Methods Standards: DoD Preferred Methods for Acceptance of Products (1996), Notice 2 (2014).

MIL-STD-11991B, DoD Standard Practice General Standard for Parts, Materials, and Processes.

MIL-STD-31000B, Technical Data Package, 2018

SAE J1739 (2021), Potential Failure Modes and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA.

SAE AS13003 (2015), Measurement Systems Analysis Requirements and RM13003 (2021) Reference Manual.

SAE AS13004 (2017), Process Failure Modes and Effects Analysis and Control Charts.

SAE AS5553 (2019), Counterfeit Electronic Parts; Avoidance, Detection, Mitigation, and Disposition, SAE International. https://www.sae.org/standards/content/as5553/

SAE AS6174A (2014), Counterfeit Materiel; Assuring Acquisition of Authentic and Conforming Materiel, SAE International. https://www.sae.org/standards/content/as6174/

SAE AS6500A (2021), Manufacturing Management Program, SAE International, https://www.sae.org/standards/content/as6500/

SAE AS9017 (2017), Control of Aviation Critical Safety Items, SAE International, https://www.sae.org/standards/content/as9017/

SAE AS9100D (2016), Quality Management Systems - Requirements for Aviation, Space and Defense Organizations, SAE International. https://www.sae.org/standards/content/as9100d/

SAE AS9102C, (2023) First Article Inspection Requirements, SAE International. https://www.sae.org/standards/content/as9102/

SAE AS9103B (2022), Variation Management of Key Characteristics, SAE International. https://www.sae.org/standards/content/as9103/

SAE AS9134 (ARP9134) (2014), Supply Chain Risk Management Guidelines, SAE International. https://www.sae.org/standards/content/arp9134/

SAE AS9136 (2016), Root Cause Analysis and Problem Solving, SAE International, https://www.sae.org/standards/content/arp9136/

SAE AS9138 (2018), Quality Management Systems Statistical Product Acceptance, SAE International. https://www.sae.org/standards/content/as9138/

SAE AS9145 (2016), Advanced Product Quality Planning and Production Part Approval Process.

SAE EIA557 (2015), Statistical Process Control Systems.

Other Publications

AIAG. Measurement Systems Analysis Reference Manual. 4th Edition. Automotive Industry Action Group (AIAG), 2010.

Anderson, D. *Design for Manufacturability & Concurrent Engineering; How to Design for Low Cost, Design in High Quality, Design for Lean Manufacture, and Design Quickly for Fast Production,* Cambria, CA, USA: CIM Press, 2010.

ASQ. "Gage Repeatability and Producibility." Adapted from The Certified Quality Technician Handbook, ASQ Quality Press and "A Study in Measurement," Quality Progress. American Society for Quality (ASQ), [accessed 2023]. https://asq.org/quality-resources/gage-repeatability

ASQ. "Quality 4.0." American Society for Quality (ASQ), [accessed 2023]. https://asq.org/quality-resources/quality-4-0

Boothroyd, Geoffrey; Peter Dewhurst; and Winston A. Knight. *Product Design for Manufacture and Assembly, Third Edition,* CPC Press, 2010.

Bralla, James G. *Design for Manufacturability Handbook,* 2nd Edition. New York: McGraw-Hill, 1986.

Bower, Keith M. "What Is Design of Experiments?" American Society for Quality (ASQ), [accessed 2023]. https://asq.org/quality-resources/design-of-experiments

CIMdata Glossary. CIMdata [accessed 2023]. https://www.cimdata.com/en/resources/about-plm/cimdata-plm-glossary

DAU IPPD. "Program Management: Integrated Product and Process Development (IPPD)." Defense Acquisition University (DAU), September 18, 2023.

Feldman, Ken. "Mastering Gage R&R: Key Steps for a Successful Study." iSixSigma, October 1, 2023. https://www.isixsigma.com/dictionary/gage-rr/

Gage R&R. Gage Repeatability and Reproducibility. Quality One International, 2023. https://quality-one.com/grr/#SnippetTab

George, Michael L., et al. *The Lean Six Sigma Pocket Toolbook*. McGraw-Hill, 2005.

Gillespie, LaRoux K. *Design for Advanced Manufacturing Technologies and Processes*. Society of Manufacturing Engineers, New York: McGraw-Hill, 2017.

Mandelbaum, Jay., Reed, Danny L. "Value Engineering Handbook." paper P-4114. Institute for Defense Analyses (IDA), September 2006

Motley, Bill. “Introduction to Variation and Variation Reduction.” Fort Belvoir, Va.: Defense Acquisition University, n.d.

National Strategy for Advanced Manufacturing, National Science and Technology Council, October 2022.

NIST Handbook 2.4. “Gauge R & R Studies.” In *Engineering and Statistics Handbook.* Section 2.4. National Institute of Standards and Technology (NIST), 2012 [accessed 2023]. https://www.itl.nist.gov/div898/handbook/mpc/section4/mpc4.htm

NIST Handbook 5. “Process Improvement.” In *Engineering and Statistics Handbook.* Section 5. National Institute of Standards and Technology (NIST), 2012 [accessed 2023]. https://www.itl.nist.gov/div898/handbook/pri/pri.htm

NIST Handbook 5.1.1. “What Is Experimental Design?” In *Engineering and Statistics Handbook.* Section 5.5.6. National Institute of Standards and Technology (NIST), 2012 [accessed 2023]. https://www.itl.nist.gov/div898/handbook/pri/section1/pri11.htm

NIST Handbook 5.5.6. “What Are Taguchi Designs?” In *Engineering and Statistics Handbook.* Section 5.5.6. National Institute of Standards and Technology (NIST), 2012 [accessed 2023]. https://www.itl.nist.gov/div898/handbook/pri/section5/pri56.htm https://www.itl.nist.gov/div898/handbook/index.htm

NIST Handbook 6. “Process or Product Monitoring and Control.” In *Engineering and Statistics Handbook.* Section 6. National Institute of Standards and Technology (NIST), 2012 [accessed 2023]. https://itl.nist.gov/div898/handbook/pmc/pmc.htm

SPC for Excel. “Five Common Mistakes with Gage R&R Studies. SPC for Excel, November 2019. https://www.spcforexcel.com/knowledge/measurement-systems-analysis/five-common-mistakes-gagerr#:~:text=There%20are%20several%20ways%20to%20analyze

Wheeler, Donald J. *EMP III Evaluating the Measurement System*. SPC Press, 2006.

White House. *National Strategy for Advanced Manufacturing*, National Science and Technology Council, October 2022. https://www.whitehouse.gov.

Websites

American Society for Quality (ASQ) https://asq.org/

DAU Cl and Cpk Calculator. Defense Acquisition University (DAU). https://www.dau.edu/tools/t/Process-Capability-%22Cp%22-and-%22Cpk%22-Calculator

Defense Advanced Research Projects Agency (DARPA)
https://www.darpa.mil/

Defense Innovation Unit (DIU)
https://diu.mil

Defense Standardization Program Office, Defense Logistics Agency
Defense Standardization Program (DSP) (dla.mil)

Digital Engineering Body of Knowledge (DEBoK), February 2022.
https://www.dodtechipedia.mil/dodwiki/pages/viewpage.action?pageId=760447627

DoD Manufacturing Technology Program (ManTech)
https://www.dodmantech.mil/

DoD Industrial Base Policy and Industrial Base Analysis and Sustainment (IBAS) Program
https://www.businessdefense.gov

Institute for Defense Analyses
https://www.ida.org

Manufacturing USA
https://www.manufacturingusa.com

Manufacturing Readiness Level (MRL) Body of Knowledge
https://www.dodmrl.org/

National Conference of Standards Laboratories (NCSL) International
www.ncsli.org

National Institute of Standards and Technology (NIST)
https://www.nist.gov/

National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership
https://www.nist.gov/mep/mep-national-network

OUSD(R&E) Developmental Test, Evaluation, and Assessments
https://www.cto.mil/

OUSD(R&E) Systems Engineering and Architecture
https://www.cto.mil/sea/

Small Business Innovation Research (SBIR)
https://sbir.gov

Systems Engineering Body of Knowledge (SEBoK)
https://sebokwiki.org/

DoD Producibility and Manufacturability Guide

Office of the Executive Director for Systems Engineering and Architecture
Office of the Under Secretary of Defense for Research and Engineering
3030 Defense Pentagon
Washington, DC 20301
osd-sea@mail.mil | Attn: Specialty Engineering
https://www.cto.mil/sea/