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# INTRODUCTION TO THE DEVELOPMENT OF A MANUFACTURABILITY ASSESSMENT METHODOLOGY

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## Abstract

There is a need for a practical, yet comprehensive method of reviewing a product design in order to ascertain the level of difficulty and risk inherent in its manufacturability. The development of the Manufacturability Assessment Methodology (MAM) is aimed at addressing this need. It is an approach that employs a series of judgments conducted by subject matter experts in an effort to understand the key elements of the product design and their impact on various aspects of manufacturing. By applying this type of evaluation, it provides a means to quantify the inherent risk of a product's manufacturability.

For typical industrial applications, the benefits of using this methodology include savings in both cost and time, which serves to enhance the competitiveness of a business and contribute to its general economic development. Similarly, the Department of Defense (DoD) Engineered Resilient Systems (ERS) program seeks to utilize this type of tool along with others to provide the capability to rapidly design, develop, test, and build trusted, flexible, and resilient systems. The U.S. Army Engineer Research and Development Center (ERDC) has developed other software tools, as well as a systems engineering framework and workflow, that supports system development from DoD Pre-Milestone A analysis throughout the life cycle of the system.

The resulting outcome of the methodology would include a metric (i.e. manufacturability score) along with identified risk areas for improvement of the manufacturability of a given design. This paper provides an introductory approach to the design of such a methodology.

## Keywords

Manufacturability, Assessment, Metric, Life Cycle

## Introduction

Development of a product design is a significant undertaking and even more so with larger, more complex designs. There are many factors that need to be taken into account but an overarching driver of product design is often cost. It is generally acknowledged that the majority of costs that will be incurred in the product life cycle are committed or locked in during the early phases of product design (Anderson, 2014). It is the design that will largely stipulate such items as material, labor, and machine requirements, all of which are associated with manufacturability. It is commonly understood that the manufacturability of a particular product or design is one of the major life cycle cost drivers (Anderson, 2014). Therefore, the ability to assess the manufacturability of a product design early in the product life cycle is beneficial to the overall product cost.

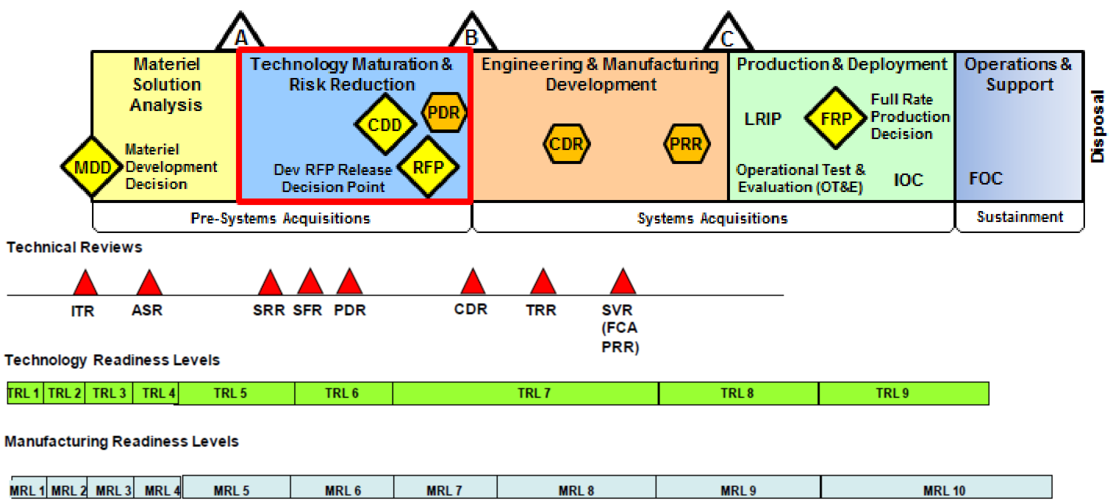
Based on the literature surveyed, there is no generally accepted assessment methodology and resulting metric for evaluating the manufacturability of a product design. In the authors' experience, companies tend to either forego this evaluation, develop an internal metric, or use whatever other industry accepted tools that are available. Such companies may experience major quality problems, cost overruns, significant delays in the release of the product design, and major customer/warranty issues as a result of areas of oversight within the design. Companies that commit to use design evaluation tools do so because they recognize the need to assess a design's manufacturability early in the design development cycle. However, their metric or tools may or may not investigate all the key criteria within the scope of manufacturability. The objective of this paper is to introduce a framework for developing a manufacturability assessment methodology focused on assisting design teams in assessing and improving product manufacturability.

This research is fundamentally aligned with the United States Department of Defense objectives to improve the quality and delivery of the products it buys while reducing costs throughout the acquisition life cycle. Accordingly, it is part of an overarching effort being addressed within the DoD Engineered Resilient Systems (ERS) initiative.

## Engineered Resilient Systems (ERS)

One of the seven stated priority Science and Technology Investment areas for the Department of Defense is Engineered Resilient Systems. As defined (Neches, 2011), *"a resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function"*. Furthermore (Goerger, Madi, Eslinger, 2014), *"for these systems to be included in the force structure, they need to be manufacturable, readily deployable, sustainable, easily modifiable, and cost effective"*. In order to accomplish the overall ERS objectives, significant contributions must be realized from numerous subsystems that ultimately determine the extent to which a system meets the mission needs of the end user. The Defense Acquisition Life Cycle Chart (DoD Directive 5000.02, 2015) shown in Exhibit 1 outlines and details an extensive collection of activities, in chronological order, that must be effectively completed in a timely manner in order to deliver products and systems to customers. From initial concept through end of life disposition, these activities can be enhanced with state-of-the-art technology and methods in order to provide for resiliency in the resultant output from the development cycle.

**Exhibit 1. Defense Acquisition Life Cycle Chart.**

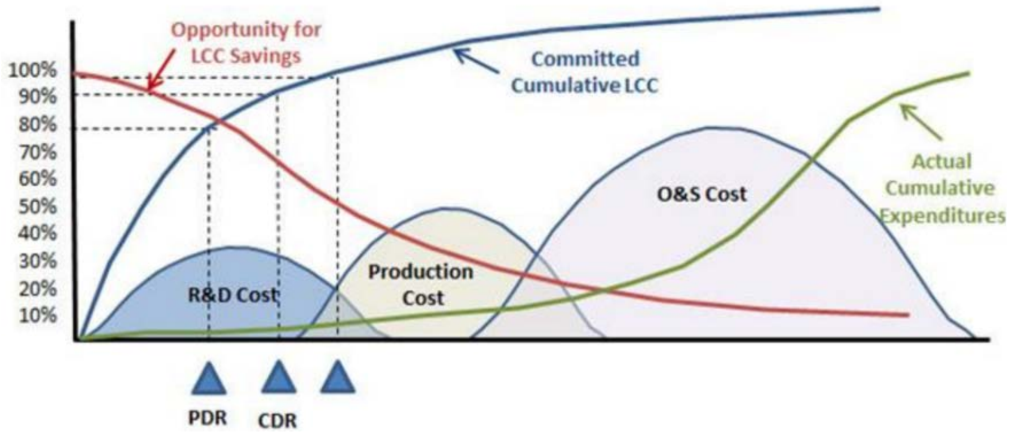



More specifically, as stated in a memorandum from the Office of the Secretary of Defense (OSD, 2011), one of the major objectives of ERS is *"to develop agile manufacturing for trusted and assured defense systems" that are "more affordable, effective, and adaptable."* In order to accomplish this objective, new and innovative methods of assessing product designs for manufacturability much earlier in the life cycle are essential.

A major thrust in ERS is the objective of controlling, and to the extent practicable, minimizing the eventual cumulative life cycle costs incurred for a product. It is generally acknowledged that design decisions made early in the initial phases drive costs throughout the ensuing life cycle as shown in Exhibit 2 (Manufacturing Management Guidebook, 2012).

The costs associated with the actual steps used to manufacture the product do contribute significantly to overall life cycle costs. However, as shown in Exhibit 2, the total cost of production is less than the operating and support costs that will be incurred during the product's functional use lifetime. Some of these manufacturing costs are driven by the product design, as specified by engineers, designers and others, and are a result of the specific processes that are designated by manufacturing plans developed by manufacturing professionals and execution of those plans by the production entity. More significantly, industry experience shows that over 80% of eventual cumulative life cycle costs are typically committed before any actual production or operating and sustainment (O&S) costs are incurred.

**Exhibit 2. Product Life Cycle Costs.**




# Manufacturability

**Background**

Manufacturability is a term used to describe the ease with which a product or component can be manufactured. Experience indicates that the more difficult it is to manufacture a product, the more costly that product is. Edwards (2002) provides an overview of such key topics as design for manufacturability (DFM), and design for assembly (DFA), and design for manufacture and assembly (DFMA). From these methodologies, different macro metrics such as production cost, time to produce and product quality are typically used to determine manufacturability. However, such metrics do not always provide for identification of the specific criteria that has the most negative effect on product manufacturability. This makes identification of ameliorative actions more difficult. Accordingly, this research focuses on a more rigorous assessment of the interaction of the most significant aspects of both the design and manufacturing in such a way as to identify specific limiting factors, highlighting them for action.

Previously, the research team conducted a literature review that revealed various methodologies for the evaluation of manufacturability. Many of these published methodologies are focused on the extraction of product geometry from CAD and use of various ways to evaluate these products. Among the various techniques applied are examples of (1) physics based models and (2) rule-based systems focused on very common manufacturing processes such as injection molding, machining, forming, etc. (Gupta, Regli, et. al., 1997 and Sabramanian and Ulrich, 1998).

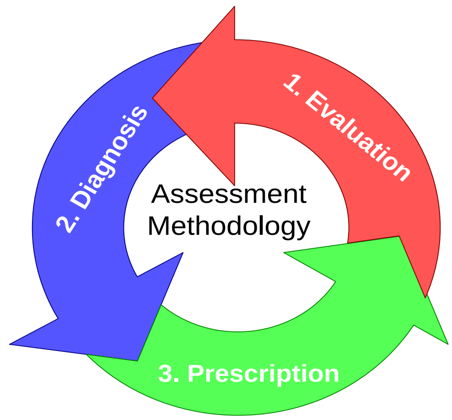
In addition to these traditional efforts, there is a need for a more holistic assessment approach. This includes such broad notions such as strategic sourcing, logistics, quality, etc. which are typically more readily available through judgments solicited from a cross functional team of experts. In addition, these judgmental methodologies are more applicable to earlier stages of the development where there is less fidelity of the product design.

The goal of this manufacturability assessment is to improve the manufacturability of the design through periodic appraisals of the product design throughout the product life cycle. In general, the assessment includes analysis of the product design, and identification of improvement actions to mitigate cost. Subsequently, after each review and actions taken to improve the design, the expectation is that manufacturability will improve, resulting in lower cost. This review is done in the context of evaluating the product design within an established framework. The global framework consists of three overarching phases – Evaluation, Diagnosis, and Prescription. The E-D-P Cycle (Walden, Greenwood, 2009) is shown in Exhibit 3.

Since the assessment is intended to be holistic, the assessment framework must in addition to an evaluation of the design, also include recommendations for improving the manufacturability. This brings in the notions of diagnosis (i.e., what are the core problems that need to be addressed?) and prescription (i.e., how will the core problem be addressed so as to effect changes that improve manufacturability?).

Once the manufacturability concerns are dealt with, then the design undergoes another assessment iteration. Therefore, the evaluation-diagnosis-prescription framework (E-D-P) may be thought of as a continuous loop operating in much the same way as the Failure Mode and Effects Analysis (FMEA) methodology. The resulting metric from an FMEA exercise, the composite Risk Priority Number (RPN), effectively establishes a baseline (as is) risk metric for each iteration of the FMEA study. With continuous improvement efforts, subsequent iterations of the same FMEA study would naturally be expected to result in lower (improved) RPN scores. Accordingly, continuous improvement in the design's manufacturability can similarly be tracked through the devised manufacturability metric.

**Exhibit 3. E-D-P Cycle.**




In order to positively impact manufacturing in such a way as to contribute to meeting the ERS objectives, a thorough analysis of the aggregate factors of both the engineered design and manufacturing processes and systems is required. While individual designs vary widely across technical fields, the general activities required to actually enable manufacture of the design are, for the most part, consistent and understood. Of course the detailed process steps will depend on the specific design criteria and the equipment and facilities utilized to manufacture the design. Essential to the successful manufacture of a product is the ability to effectively manage both the technology required by the design and the technology inherent to the specified manufacturing processes. The DoD (MRL Deskbook, 2015) has published the Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs) shown in Exhibit 4 that effectively define the successive development levels that, once reached, enable this to be done. Ideally, this is the purpose of the traditional formal engineering design review process. It typically includes concurrent engineering activities, with program management holding periodic formal reviews (e.g. conceptual, preliminary, and critical) at key stages of the research & development and initial production phases of the product life cycle. However, in the experience of the research team, there are times when the rigor with which these formal reviews are conducted is lacking. To satisfy this need, a detailed assessment methodology such as the one described in this research would serve to benefit the DoD and commercial industries in their efforts to understand and mitigate manufacturability concerns and cost drivers throughout the produce life cycle.

The commitment of product costs early in the development process phase, suggests strongly that typically smaller improvements in manufacturability are possible as the design moves toward maturity. Product Design Maturity within DoD is expressed through typical milestone gates as shown in Exhibit 5 (McCall, T., Walden, C., Dalton, L., et al, 2016): Milestone A (Concept), Milestone B (Prototype), and Milestone C (Low Rate Production) subsequently moving forward to Full Scale Production. It is reasonable to expect diminishing returns on the impact of the manufacturability assessment as one moves toward greater levels of design maturity due to the higher level of cost commitment.

**Exhibit 4. TRL and MRL Levels.**

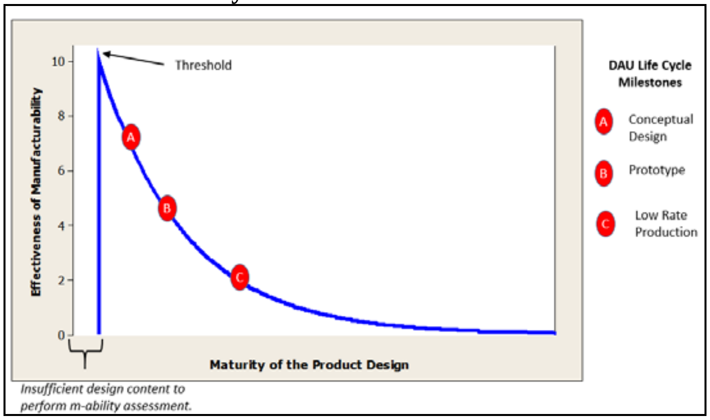
There are nine TRLs that indicate the technology maturity levels as follows:

- **TRL 1**: Basic Principals observed and noted.
- **TRL 2**: Technology concept or application formulated.
- **TRL 3**: Experimental and analytical critical function and characteristic proof of concept.
- **TRL 4**: Component or breadboard validation in a laboratory environment.
- **TRL 5**: Component or breadboard validation in a relevant environment.
- **TRL 6**: System or subsystem model or prototype demonstrated in a relevant environment.
- **TRL 7**: System prototype demonstration in an operational environment.
- **TRL 8**: Actual system completed and qualified through test and demonstration.
- **TRL 9**: Actual system proven through successful mission operations.

There are ten MRLs that are correlated to the nine TRLs in use.

- **MRL 1:** Basic Manufacturing Implications Identified.
- **MRL 2:** Manufacturing Concepts Identified.
- **MRL 3:** Manufacturing Proof of Concept Developed.
- **MRL 4:** Capability to produce the technology in a laboratory environment.
- **MRL 5:** Capability to produce prototype components in a production relevant environment.
- **MRL 6:** Capability to produce a prototype system or subsystem in a production relevant environment.
- **MRL 7:** Capability to produce systems, subsystems, or components in a production representative environment.
- **MRL 8:** Pilot line capability demonstrated; Ready to begin Low Rate Initial Production.
- **MRL 9:** Low rate production demonstrated; Capability in place to begin Full Rate Production.
- **MRL 10:** Full Rate Production demonstrated and lean production practices in place.

**Exhibit 5. Impact of Product Maturity on the Effectiveness of the Manufacturability Assessment.**



The curve in Exhibit 5 (McCall, T., Walden, C., Dalton, L., et al, 2016): represents the proposed relationship between the effectiveness of the manufacturability assessment as a function of the maturity of the product design. This is not to assume that a manufacturability assessment for a product already in either low rate or full scale production is not a helpful and worthwhile activity, but that the biggest impact tends to occur earlier (milestone A and B). The issue at milestone A and to some degree in milestone B is the relatively small amount of design detail that is available for detailed analysis and review. As various design options are being evaluated early in the development cycle, there is a need for a quick and responsive manufacturability assessment to provide guidance on the subsequent decisions. At this early stage the precision in the manufacturability assessment is not as critical because the improvement potential is relatively large. Generally speaking, the ability to assess the manufacturability of a designed component in a meaningful way is a function of the technical information available for consideration during the assessment by a subject matter expert (SME). The more complete a design is, the better the assessment should be. Likewise, the more capable and complete the manufacturing processes for producing the component are, the better the associated manufacturability risk assessment.

However, even when the design and manufacturing processes are completely defined, the credibility of a completed assessment is dependent on the performance of the involved SMEs. Such assessments are compiled from the comprehensive qualitative judgements pertaining to specific aspects of the engineered design in relation to the specific aspects of manufacturing. A well designed assessment instrument may not yield a meaningful output when used by an inexperienced individual that has assumed the role of an SME. Likewise, a competent, professional SME may struggle with conducting a meaningful assessment when using a poorly designed instrument.

This research focuses on the initial steps of development of a practical and effective manufacturability assessment methodology. The intent is to create a method to assess the effects of specific identified associative factors in such a way that problems inherent to the manufacturability of a design are subjectively evaluated. Such effects may then be assessed at various stages of the product life cycle.

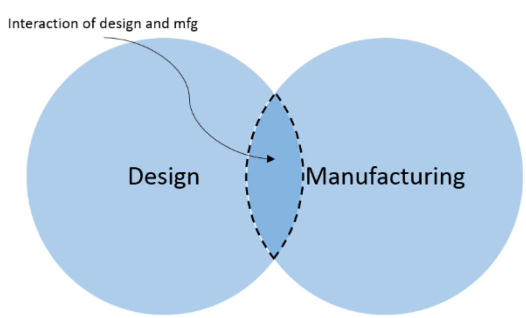
The developed methodology includes the means used to evaluate the design, and anchoring factors for qualitative and quantitative scoring of the metric criteria. The assessment method is developed in a manner that once the evaluation is complete, it provides for diagnosis of the core manufacturability problems. These are the problems that prescriptive recommendations must address in order to improve the manufacturability of the design.

**Manufacturability Factors**

The manufacturing process is complex and impacted by many factors of a design. Similarly, the design process is large in scope and involves defining factors across many functions in order to deliver a product that satisfies the customer requirements. These factors have the ability to disrupt the operation of a manufacturing facility, potentially increase cost, and reduce the overall quality of the product.

There is inherent difficulty in development of a comprehensive list that embodies all of the factors affecting manufacturability. However, this is essential input for a meaningful assessment. Exhibit 6, illustrates this idea of an overlap or interaction between design and manufacturing. The key is to identify the factors of the design that have impact on manufacturing. However, due to the broad and complex scope of both the design and manufacturing processes, this is not a simple task.

**Exhibit 6. Design to Manufacturing Interaction.**




It is proposed that the overlapping area shown in Exhibit 6 be used as the basis for determining the areas of interaction between design and manufacturing. This information could then be used to defne the taxonomy to be used for the assessment methodology. An example of this idea is illustrated in Exhibit 7, which focuses on potential factors, or aspects, of design and manufacturing and their interaction between one another.

**Exhibit 7. Interaction Matrix Example.**

| Aspects of Design (AD) / Aspects of Mfg (AM) | Material | Ease of Assembly | Part Geometry | ............ | ............ | ............ |
|---|---|---|---|---|---|---|
| Process | X | X | X | ... | ... | ... |
| Supply Chain | X | X | X | ... | ... | ... |
| Quality | X | X | X | ... | ... | ... |
| ............ | ... | ... | ... | ... | ... | ... |
| ............ | ... | ... | ... | ... | ... | ... |

In conducting the assessment, an SME would rate the impact of each aspect of the design (e.g. material) on each aspect of manufacturing (e.g. process) to determine the manufacturability score (i.e. judgement) for that interaction. Every feasible interaction would then be similarly considered. The following are examples for consideration:

- What is the impact of ease of assembly (aspect of design) on quality (aspect of manufacturing)?
- What is the impact of part geometry (aspect of design) on process (aspect of manufacturing)?

In addition to the rating of each of the cells in the manufacturability matrix, several challenges relative to scoring the SME judgements exist. These include:

- How to weigh the relative importance of the different interactions?
- To what extent (i.e. score fidelity) will the SME be able to distinguish between low and high manufacturability judgements?
- How will individual scores be accumulated to reflect the manufacturability of a component? Of multiple components that form an assembly?
- What is the preferred way to communicate the cumulative manufacturability scores to others?

These challenges can be considered and thoroughly evaluated in future research.

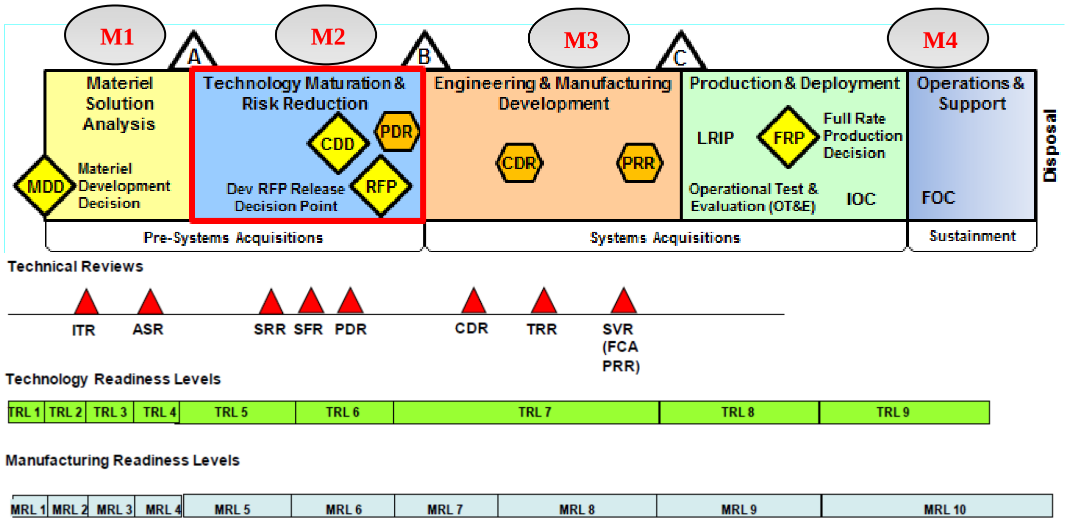
**Potential Life Cycle Stage Assessments**

The manufacturability assessment, thorough subjective appraisal, conducted by qualified SME's provides feedback at key critical points in the product life cycle to engineers, designers, and other responsible personnel concerning the level of difficulty involved with manufacturing the product to adhere with all applicable engineering requirements in the volume necessary to meet customer delivery requirements. Exhibit 8 shows the strategic timing of four such potential assessments during the DoD acquisition life cycle (DoD Directive, 2015).

A *general manufacturability assessment* (ref: M1 & M2 in Exhibit 8), based on preliminary design concepts/criteria and previously demonstrated manufacturing capabilities may be conducted before a specific manufacturing facility for a given product is established (ref: MRL 1-6) in order to identify potentially problematic design specifications and/or manufacturing processes. A *process and design specific manufacturability assessment* (ref: M3 in Exhibit 8) can be conducted with respect to a known specific manufacturing facility and a production released engineering design (ref: MRL 8-10 & LRIP) in order to assess the current baseline manufacturing capabilities for a product.

Some manufacturability issues may not become evident until the very latter stages of the product life cycle, long after the product was produced and well in to a product's useful life. In a worst case scenario, such issues may involve a manufacturer's recall, product liability, and other extremely costly outcomes. Nonetheless, the relevant issues may have been avoidable if identified before the product was manufactured. In such cases, a *sustainment manufacturability metric* (ref: M4 in Exhibit 8) at that point in time is useful. The timing of these assessments also coincides with the MRL proposed technical review points shown in Exhibit 8.

**Exhibit 8. Potential Assessments During the Product Life Cycle.**




The final calculated manufacturability metric for an individual component or an assembly of multiple components would then be available for consideration in regards to a variety of purposes.

Anticipated beneficial outcomes of considering the metric at various stages of the product life cycle would include, but not be limited to:

- Better determination and mitigation of risk associated with manufacturing the product
- Reduction of costs associated with manufacturing the product and subsequently reduced life cycle costs
- More considered Make/Buy Supply Chain decisions
- Better supplier selection decisions
- Better manufacturing process decisions
- More consideration of manufacturability affecting design decisions, earlier in the life cycle
- More focused manufacturability discussions during formal design reviews
- Better determination of product manufacturing and technology readiness (ref: TRL & MRL) at the stage in the life cycle where the assessment was conducted
- Enhanced engineered resilience through early life cycle proactive concurrent engineering input

The expectation is that by using such a structured approach to a review of manufacturability issues, resulting in a meaningful, quantifiable metric, the specific limiting elements that affect the manufacturability of a product can be better targeted for research and improvement actions. This approach provides for continuous improvement activity throughout the product life cycle.

## Conclusions

This paper has focused on introducing a new approach for understanding and evaluating the manufacturability challenge. This work introduces a proposed assessment framework and as well as the notion of a proposed metric that may be potentially useful for practitioners and managers. This notion could be used by managers to drive product development teams to develop designs which are more manufacturable and ultimately products which are less costly. This is in alignment with the Department of Defense's ERS program which targets the reducing the overall procuct life cycle costs. Finally, this serves as the foundation for other works to develop a more detailed methodology that will enable validity and reliability concerns to be defined and explored. It is the eventual goal of this work to develop a mature assessment methodology, which can be used by engineering managers to guide research and development programs.

## References

Anderson, D.M. (2014). *Design for Manufacturability: How to use Concurrent Engineering to Rapidly Develop Low-Cost, High-Quality Products for Lean Production*. Boca Raton, FL: CRC Press.

Edwards, K.L. (2002). Towards more strategic application of product design for manufacture and assembly: priorities for concurrent engineering. *Materials & Design.* 23(7), 651-656.

Goerger, S., Madni, A., Eslinger, O. (2014). Engineered resilient systems: a DoD perspective. *2014 Conference on Systems Engineering Research.* 28, 865-872.

Gupta, K., Regli, R., Das, D., Nau, D. (1997). Automated Manufacturability Analysis: A Survey. *Research in Engineering Design*. 9(3), 168-190.

McCall, T., Walden, C., Dalton, L., et al. (2016). Manufacturability assessment methodology for reducing life cycle costs. Engineering Research Development Center. (Pending)

Neches, R. (2011). *Engineered Resilient Systems (ERS), S&T Priority Description and Roadmap*.

Office of the Secretary of Defense. (2011). *Memorandum on S&T Priorities*. Washington, DC: U.S. Government Printing Office.

Subramaniam, B., Ulrich, K. (1998). Producibility analysis using metrics based on physical process models. *Research in Engineering Design*. 10(4), 210-225.

United States Department of Defense. (2012) Manufacturing *Management Guidebook for Program Managers* (Chapter 1, Section 1.3.1). Washington, DC: U.S. Government Printing Office.

United States Department of Defense. (2015) *DoD Directive 5000.02.* Washington, DC: U.S. Government Printing Office.

United States Department of Defense. (2015). *MRL Deskbook (v2.4).* Washington, DC: U.S. Government Printing Office.

Walden, C.T. and Greenwood, A.G. (2009) Assessing small and medium manufacturing enterprises: a taxonomy based approach. *2009 American Society of Engineering Management Conference Proceedings*.

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